# PHYSICS

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## A TEXT-BOOK FOR SECONDARY SCHOOLS

BY

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# PREFACE

At this date the teachers of Physics in secondary schools are confronted with an embarrassing wealth of manuals and other guides for the work of their classes. The multiplication of such aids is one natural consequence of the full acceptance that Physics has found in recent years, as an almost indispensable part in the opportunities offered to pupils of that grade. The fact is also a significant witness to a healthy striving toward excellence among those interested in Physics, in order that the newer subject may sustain favorable comparison with the standards of the older tradition, as regards the nourishing quality of its matter and its methods.

Considerations like these are to some extent a ready-made apology for each renewed attempt to get closer at a few points to the requirements of a situation that is developing even now under our hands, and revealing unexpected elements of strength. Yet, as the problem comes nearer to satisfactory solution by the joint labors of many earnest minds, the demand grows sharper that a new book shall justify its existence. The clearest justification of an enterprise like the present one can appear only later, should its usefulness finally stand proven. On that score no claim can be urged at the time when a book is launched, though our hopes run high. But it seems proper, nevertheless, to go so far as to set forth somewhat

explicitly the grounds for entertaining any faith that the following pages may be recognized as a serviceable contribution in their particular field. The most fitting mode of speaking to that point which occurs to me is a less direct one; I shall try to explain the intention with which the plan of the book has been conceived. And, since this Preface contains essentially all that I offer in lieu of special Directions to the Teacher, the form of statement chosen recommends itself by serving a second purpose. It provides in some sort a key by which to decipher the reasons that have governed the selection and arrangement of the material, and which ought to be laid before the teacher for his information. Unless those reasons appeal strongly to him, the book can scarcely prove fruitful for his use, because the text — in all experimental science, at least — is so much less important than a capable teacher, that no book can be good *for him*, when it hampers decidedly his spontaneous activities. Neither can classes be expected to thrive where the instruction is not given in sympathy with the author's point of view; and, consequently, that point of view should be announced plainly. But when concessions are needed, the teacher must mould the text to his uses of it; the book must not aim to bend him to the writer's way of thinking.

This elementary course in Physics is designed for young people from sixteen to eighteen years of age, who are nearing the close of their training in a secondary school. It has been written with a strong sentiment of respect for the audience, as well as with sincere concern for this particular phase of the subject. The task would not have been undertaken without an honest belief that these two primary qualifications for it are present; and both feel-

ings blend into the desire that Physics should work out a sound and characteristic pedagogy, as a means of cultivating solid mental fibre in those who study the science. In order to hold its place strongly, Physics must be adapted to the purposes of the school, and be made to yield its full educational value; moreover, other things being equal, that value will be greater if the instruction in Physics adds new elements of discipline and insight to those derived elsewhere. This thought has been allowed full weight in setting the bounds and placing the emphasis of the treatment, about which some things ought to be said in detail, on several points that offer themselves.

In these days we need not insist that reasonable success in teaching Physics can be commanded only where a good school-laboratory is available as an adjunct. No other arrangement is to be contemplated seriously, than one which supports the instruction upon an extended acquaintance with phenomena through experiment and observation. Therefore, if this is proposed as a text-book, in the terms of the subtitle, nothing is implied in the name but a more closely limited purpose, which relinquishes completely the function of guiding experimental work, and furnishing practical hints and directions for use in the laboratory. My personal conviction is thus deliberately registered, that the best interests on every side are served in this separation. Wherever laboratory-manuals independent of the text-books are introduced, the pupils are likely to gain in capacity and self-reliance, through the necessity of selecting and stating for themselves the facts to be matched with reasoning and discussion, instead of following closely set and unmistakable finger-posts of suggestion to the results. As regards the

text-book itself, too, it seems as though that must be improved, and acquire a more effective unity of subject-matter and of general tone, by casting out the remnant of directions how to carry on experiments that has been retained only as a compromise. The directions are often too meagre to be satisfactory, and yet sufficiently long to break up a connected sequence of ideas into desultory items. In the light of this commentary, the fact that the text-book does not enlarge upon forms of apparatus and their uses becomes a declaration touching the coördinate importance of experimental work for the instruction, and an acknowledgment that any adequate handling of those matters must be fuller and more systematic than would be practicable here.

Conceding that pupils should learn to see what is happening under their eyes, and acquire at first hand a definite knowledge of phenomena as a preparation for further discussion, it has seemed right to omit pictures of what is thus seen, as superfluous, or even likely to prove harmful. For it "saves time" to use an illustration on the printed page, instead of a piece of apparatus on the work-table; and the temptation is to substitute the picture for the experiment, without stopping to reflect that we are running counter to the main tenet of our scientific creed. It is hoped that diagrams have been spread liberally enough in the present text to assist the thought wherever that form of aid is necessary. But, knowing it is expected of pupils — to mention only one example — that they should see convection-currents in a heated liquid, why should the weaker pictorial form of that familiar phenomenon be added? The idea here suggested has been followed ɔnsistently.

The remark is pertinent in this connection, that the necessary coördination of experiment and text, upon which we are here laying so much stress, is the most delicate and difficult pedagogic problem of Physics. No printed words can embody the patient tact that is required to impart information as to ascertained results of long standing, and at the same time implant the spirit of an inductive science. Yet the characteristic discipline of Physics lies in the union of firm and tenacious grasp upon what is known, with suspended judgment upon undecided issues; of cautious accuracy with undamped enthusiasm. From the first stage onward, the learner should not only assimilate the positive results of Physics, but should also be led to realize something of the methods by which territory now held by the science was explored and occupied.

It is comparatively easy to convey information dogmatically; and even to interweave experiments with that procedure, quoting them in support of a principle *after* announcing it. To be sure, a plausible plea can be advanced here, that this method presents Physics on its deductive side, which has been so fruitful of results; yet the use of experiment by way of explanatory postscript to verbal exposition scarcely exemplifies the same spirit as an appeal to facts for the final test of prediction according to a deduction. However, granting a fair concession to any claim which might be made on this score, we must remember that induction is *primary* in experimental science, and not merely complementary. To renounce that process in favor of deduction, simply because of difficulties in execution, is cutting the knot indeed; but we should then sacrifice the best value of our subject for the

school, and reverse the essential attitude of mind in undertaking it. Living examples encourage us to persevere, rather, in seeking a fuller solution of the problem; there are science-teachers who prove that it is possible to arrange phenomena as a prelude from whose study an important principle can be divined, the selected line of approach to it being made to appear natural, and even spontaneous on the part of the pupil.

It must be allowed, in order to present the situation candidly, that the most generous provision of school experiment will often fall far short of the amount and quality requisite to establish securely an induction. And the gap will be unnecessarily wide unless class-room experiments are used liberally as a foundation for the narrower laboratory exercises of the pupils themselves. The teacher's aid in several forms is indispensable, of course, because phenomena will fail to teach their lessons to an inexperienced mind, with the wisest devising of details in the instruction. But, if given sparingly and with discretion, that aid is found to consist largely in pointing out stepping-stones for the pupil's own logic; that is, in stimulating him to self-help. Under such stimulus, he may retrace historic steps of progress and be cultivating a spirit of sympathy with the work of original discovery at the same time that he is acquiring knowledge.

The parallel use of text-book and some laboratory guide has been advocated at length in the considerations already put forward; and it is part of the plan to leave a wide option in working out the experimental accompaniment to this text, as well as a free field to any good laboratory manual. The preferences of the teacher for particular experiments, and the facilities with which the school lab-

oratory is equipped, are determining elements that cannot be overlooked. But references to experiments could not be omitted here without infusing a character of vagueness into the treatment of the subject-matter. So an *Outline of Experiments* (see Contents) has been appended, and their points of connection with the various topics have been indicated, both in the list, and in the body of the text. This Outline is intended to show: (1) the places at which support from experiment is clearly advisable; (2) the types of experiment that furnish a reasonable basis for particular ideas.[1]

In such matters one school may profitably vary from another, and the list of experiments for the same school should be modified from year to year; especially it should be enriched with alternatives and additions continually, in order to increase the available stock from which good material may be drawn. A permanent set of say forty experiments, however weightily authorized, means death to the living spirit of laboratory teaching.

On consulting the list here furnished, it will be seen that the choice has not been limited to exercises suitable for individual work in the laboratory; class-experiments are suggested as well, to be shown by the teacher and made topics for discussion in the class-room. My experience proves beyond reasonable doubt that elementary instruction in Physics suffers where contact with phenomena and with experimental methods is confined to a small group of "quantitative" experiments; the possibilities of the class-experiment have not been fully exploited.

[1] In a few cases an experiment is suggested by the mark "(Ex.)" without a number, where its character is sufficiently described in the text itself.

Each experiment in the list is so far described as to identify its general plan, and current laboratory manuals are referred to occasionally where they furnish especially useful suggestions. Somewhat greater detail is supplied for a few less familiar forms of experiment.

Engineers and electricians are prone to assume that the chief aim of Physics is to formulate systems of units, and methods of measuring quantities that are of prime importance in their practice, — such as force, energy, and power. Physicists by profession are likely to feel preferences for some outposts of modern discovery, or to concentrate their interest upon the theoretical, abstract phases of the thought. But neither form of narrowed emphasis can be accepted in a book addressed to a school audience. Instead of feeding them with crumbs from the specialist's table, Physics for the school must be treated in relation to the average boy and girl, approaching the threshold of active life.

Now the aims of the secondary school are not specialized; every subject taught in them should be freighted with liberalizing influences. So, though Physics has a theoretical and mathematical side, and though, as an older science, it has taken on in parts a character of formality and fixedness, these elements must not be exaggerated out of true proportion. The several aspects can be made to fall into a broader and juster perspective. They can be subordinated in the view of Physics as a gradual product of human effort, its thought embracing no inconsiderable share of our recorded success in the endeavor to come to intelligent understanding of the world about us. The truest friends of Physics — and among them should stand the writers of text-books —

will insist most strongly upon the refusal to conceive it less inclusively for the uses of the school.

This one idea is really a theme that can be worked out in several ways; indeed, its plainer consequences have been accepted consistently as my guide, while shaping the outlines of the present book, wherever any question of consciously abandoning the traditional plan arose. An itemized list of such departures would possess no interest; it is perhaps enough to say that they flow from a deliberate policy, and to suggest more specifically, as instructive to those concerned, a comparison on three general lines, to which attention is directed below.

I. The concise and connected description of physical phenomena requires a language of more accurate terms than our everyday speech supplies. The meaning of such terms cannot be left to vague, colloquial usage, but is a matter of settled agreement, recorded in the definitions of physical quantities, or, more generally, of physical conceptions. In using this special language, it is important to associate habitually their proper sense with the words; whether they be familiar, but having preciser meanings for the purposes of Physics, or be brand-new inventions. Experience teaches us to appreciate the difficulty with which beginners learn to attach clear ideas to the commonest conceptions of Physics. Hence care has been exercised to avoid slighting the explanation of such physical terms as are introduced; on the whole, more space than usual is devoted to defining them, and pointing out what ideas they involve, how their ordinary meanings have been sharpened, or why the need of them came to be felt.

At the same time the attempt has been to make each

term of the technical vocabulary prove its case (so to speak) before admitting it here. For if we assume that the value of a physical conception is to be estimated according to the usefulness of it, is there any good reason for asking a beginner, who is a student of general aims, to exceed the equipment of this kind that is demanded within his own range? Have we not all seen instances that suggested David in Saul's armor? Allowing such a distinction between the needs of special or advanced students and others, it is made effective here in two ways: (1) by including explanations of those physical ideas only which fall within the scope of the text; (2) by offering explanations in no more general form than is called for by the applications and illustrations that are fairly covered by our treatment of the subject.

It ought to be said outright, perhaps, though the book speaks plainly for itself in this respect, that these limits are not imposed in order to make Physics easy, but as a ground for demanding thoroughness from the pupils. The selection of material for the following chapters is based upon a duly digested interpretation of personal experience as to what young people of eighteen can do and what they cannot do. There is no need to shirk difficulty of the right kind; they handle Euclid and Greek grammar well; but we ought not to ask them to breathe a thick atmosphere of technical Physics suddenly. So I have ventured to leave unmentioned such matters as the C. G. S. system of units, the kinetic theory of gases, absolute temperature, and the wave theory of light. Of course, one precaution must be observed where we content ourselves with a conception at something less than its broadest statement; a later revision should be possible

by *extension* rather than by *correction*. It is thought that this point has been sufficiently guarded, and that the text is fairly accurate Descriptive Physics as far as it goes.

II. The simpler measurable relations among physical quantities have been insisted upon without flinching, the aid to clear understanding being fully realized, which can be derived from quantitative definiteness, and even from the quasi-quantitative efforts of a beginner's measurements. But the main object to be kept in view is to provide exercise and training in physical thinking; lines of mathematical reasoning are to be found elsewhere in the school-course. Hence the statement of principles in mathematical form has been confined almost without exception to such empirical rules as can be connected with some of the experiments that are introduced. For a mere dogmatic announcement of a quantitative law, followed by numerical applications of it, gives practice in calculation, it is true; but the time assigned to Physics can be applied with greater profit to cultivating logical power in dealing with phenomena.

In further pursuance of the idea that reliance upon experiment and observation should be first developed, and the habit formed of keeping conclusions within the bounds that facts warrant, — this is the discipline characteristic of science-study, — pains have been taken to minimize and subdue the tendency toward hasty adoption of a theoretical point of view. It would be pedantic, doubtless, to exclude from this first stage all reference to examples where facts are correlated by imagining a mechanism whose existence is unverified. It cannot be denied that such matter has found place here and there in the book; but theoretical statements are as a rule postponed as lying

beyond our borders just now, and those which do occur are duly set apart, and surrounded with proper safeguards against loose acceptance of them.

III. Something has been done toward relieving the impression that Physics has always been just as we find it now, with modes of formulating its principles that are apt to appear arbitrary to the learner, if considered apart from any notion of evolution in the science; that is, of growth and development reaching greater scope, certainty of knowledge, and formal accuracy. So much is now regarded as instinctive by the individual, because he absorbs it too early to remember the process, that it opens a new horizon to see how *everything* had to be discovered, and worked into its present shape, often after many unsuccessful trials.

The historical element is to be prized on other grounds than the one just mentioned. To demand of young people, as part of their attainment, some acquaintance with the men who have made fundamental contributions to Physics and with the epochs of marked advance, allies science with the humanities, supporting (as we should) the influences of secondary schools for culture. Matters of this weight are not adequately presented by inserting an occasional date or a name in a foot-note; and yet they could not be dwelt upon at length without interrupting the thought or encroaching upon the available space. So where questions of biography or history become prominent, and where a topic seems to deserve expansion for some special reason, books are indicated in which such material can be found. This is done in the *References to Collateral Reading* (see Contents). It is desirable on all accounts to encourage the recognition, especially in alert

minds, that Physics is a *subject*, and that it does not lie between the covers of one small book.

Coupled with clear convictions of long standing on many such heads, there is present to my mind a strong realization that the practical difficulties of doing are not altogether resolved by knowing what ought to be done. The possession of a chart which lays down shoals and reefs is in so far helpful; but to steer in the open channel among doctrinal extremes remains as a problem of navigation. In this case, the sense of security that the clews of pedagogic progress for Physics are visible is united with a moderate estimate of my success in following them. The specific enumeration of various aspects in the situation, which has made this Preface long, is essentially an invitation to consider them attentively; only to a minor degree is the conclusion implied that the text here published improves upon its predecessors.

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UNIVERSITY OF CALIFORNIA,
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## MAGNETISM AND ELECTRICITY

### CHAPTER XVI



### CHAPTER XVII



### CHAPTER XVIII

# INTRODUCTORY[1]

1. If we enter upon the study of Physics thoughtfully, it is natural that some questions should arise at once about the reasons for taking up this science, and the gain to be expected from it. Such questions are not to be put aside, for it is clearly an advantage to approach any new subject with even a glimpse of insight into its aims and methods. So the suggestions to be made here are meant to encourage an intelligent view of Physics, and to give right direction to our effort from the outset. It is true that the fuller answers to questions of the character referred to should not be attempted in advance; the study itself may best supply them as we proceed. Nevertheless, some preliminary ideas bearing upon the points named can be put forward and understood. These will aid in securing the right attitude of mind, without unduly anticipating that more intimate knowledge which is still to be gathered from what follows. We shall introduce a few simple ideas applying to Natural Sciences as a group, before speaking more particularly of Physics.

2. Everybody is aware that the common routine of our lives brings us into contact with many occurrences and

[1] The bearing of these introductory remarks can be made to appear as the work of the year progresses, by returning to them with fresh illustration from time to time. They are intended to strike a key-note for the pupils; it is hoped that the teacher will read the Preface for the sake of such suggestions as it contains about the general plan of the book.

processes among the objects around us. We are collecting experience of this kind continually through oral and written accounts from other persons, as well as through direct impressions upon our senses. The sensations of sight, hearing, and touch are here especially prominent. This is an important first step in the path of scientific inquiry; and it is taken by all of us alike. In more formal phrase, we describe these activities as "observing the phenomena of nature." A **phenomenon** is literally something showing itself to our perceptions. Yet any individual among us is at best apt to meet with series of events that seem unrelated and disconnected; watch the ordinary happenings of a day for illustrations of this. In the case of a given person they include only broken sequences of what we call cause and effect, and they are in other respects fragmentary. Such fragments of natural phenomena, however, when pieced together, form the indispensable basis of the natural sciences. These are concerned with nothing less than the whole body of current knowledge about animals and plants, for example; or the earth and its atmosphere; or the industrial contrivances of civilized men. Their range embraces our collective experiences in matters similar to those just instanced. Such experience has been slowly accumulated as an international possession and recorded during many generations. One feature of the ideal set before any branch of natural science is that it shall finally come to be complete, and cover the ground thoroughly within a certain assigned province. Seen from this side, a student's pursuit of these sciences only carries on more steadily and effectively a training which life is forcing upon all of us — learning about the properties of things by means of impressions upon our

senses. It is one good point scored at this stage if the study of science is thus made to appear a task that is not entirely novel and strange. Every one has some preparation to undertake it, and has acquired, unconsciously or deliberately, a respectable store of information that can be turned to good account.

3. The wider inclusion of facts, though, is not the single aim in these fields of inquiry. The data are also to be sorted and arranged, very much as the books of a library need to be indexed and catalogued. Not to speak of any deeper reasons, this must be done in order that the facts may be held with less strain upon the memory. Our resources of information are always made available for various uses and wielded more easily, when they are kept in some orderly connected way under suitable headings. So another form of activity for the natural sciences is here implied, beside the gathering of material. The first help toward handling the raw product of observation is found in classifying it. To classify is to devise, as it were, some proper system of labels and pigeon-holes, and sort into smaller groups on that basis. By a kind of mental analysis, phenomena are scanned to find such traits of likeness and difference as appeal to our minds, and associated in groups accordingly, with a view to economy of effort in our subsequent command of them.

4. First, the various sciences are set off for separate treatment by application of this idea. Their provinces are assigned to them, we may say, partly by way of concession to our limited powers, in order that the larger problem of description may be taken up piecemeal. For even the strongest and best-trained minds would be bewildered in attempting to describe, within a single syste-

matic scheme, the entire mass of natural phenomena in all its extent and complexity. So the special conditions of plant-life are studied as Botany; the structure of the earth's crust and changes in it fall to the share of Geology; what is known about the planets and the stars furnishes the material of Astronomy. In these examples, then, it is seen that the lines of division between the sciences recognize certain broad features of difference in subject-matter and point of view as the ground for this partition of one natural science into several constituent sciences. The scope of Physics is not easily indicated in a sentence. And there is the less need to try, because the detailed study of the subject, upon which we are about to enter, offers the best opportunity to ascertain just what physical science includes. We do know that it touches everyday life at many points, since it reaches wherever there are machines, and phenomena of heat, sound, light, and electricity. A gain of insight into such matters as these is the reward held out for our encouragement.

5. In the second place, simplicity and clearness are further sought within any one science by admitting subdivisions, each of which comprises a narrower range of similar items. Mechanics, Light, Sound, Heat, and Electricity are standard headings in Physics, under which those results are considered in closer connection, which are in practice often brought to bear upon related problems. The lessons conveyed under the title Mechanics aid toward the understanding of all machines. An acquaintance with the general behavior of light enables us to trace the action of mirrors, prisms, and lenses in various combinations like telescopes and cameras. The main types of electrical contrivances are presented under Electricity;

and attention is given, in the study of Sound, to the more special phenomena of musical instruments.

When we have once perceived that the divisions and subdivisions of natural science originate in our ways of thinking and our limitations, we shall cease to expect that these boundary lines are respected in the workings of nature. As a matter of fact, of course, phenomena remain closely linked in the time and place of their actual occurrence, even though they have been picked out and allotted separately to Chemistry, Physics, Botany, or Geology. Just so plants continue to grow side by side in the fields, after the botanists have segregated them into orders, genera, and species. Neither should we ourselves respect the distinctions between sciences, or between parts of a science, unless they serve our purpose best. In the following chapters, for instance, we have adopted the order that seems most instructive on the whole. This fails to put into one compartment all that is usually labelled "Mechanics." But it is the truer for that failure, since the principles of mechanics run through much of Physics and appear at many points, whether we will or not.

**6.** Physics rests upon the same foundations as other branches of natural science. At every stage, knowledge is gained by noting and classifying phenomena. The frontier of discovery is pushed forward to-day as it was in the earliest beginnings of which we have record — by finding out first *what happens*. One consequence of comparing many special cases is the detection of general rules under which all of them can be included. To that extent, such rules summarize certain portions of our experience, or certain aspects of it. They are often called **principles**, or **laws**; but if the latter word be used, do not think of it

in the legal sense. The "laws of nature" (so-called) are short statements of what is found to hold true in groups of similar cases; they are not passed by any legislative body. General rules in the process of making are illustrated in the following examples; they serve our present purpose none the worse if they are not final, nor completely accurate: —

(1) Unsupported objects fall to the ground.
(2) Rainbows are seen opposite the sun.
(3) Trade-winds blow from the northeast.
(4) Days are longest in June, and shortest in December.

**7.** But it is intended that our rules or principles should do more than render manageable the experience that is already gained. In these matters we have learned to rely upon the past and present for the pattern of the future. That is, the rules as they are framed should enable us to forecast consequences, because we have become convinced that phenomena can be repeated when the proper conditions are fulfilled. The practical application of Physics depends largely upon accurate foresight of what is going to happen in given circumstances. And close approach to certainty has been attained in many directions; a steam-engine, or dynamo, or telescope, or pipe-organ, or blast-furnace can be planned in advance, nowadays, its performance when constructed being predicted to a nicety by known rules or principles. Yet the united contributions of many great men, and the busy exercise of their best thought, have been required to bring us to this point. That lesson is impressed on us in reading scientific history, even within the limits of the references that are given in this book.

Early attempts at formulating rules have often failed,

or seemed to fail; new phenomena appear, and contradict our anticipation in part or altogether. Refer, for instance, to the four illustrations at the end of § 6. We see balloons rising, instead of falling to the ground; explorers have found "southeast trades," and longest days in December; colored bows (halos) are observed close to the sun, as well as in the opposite region of the sky. Without much special knowledge of Physics, it is easy to add examples where later experience corrects previous inferences, or pieces out conclusions. Finally, progress comes out of conflict between expectation and fact. Thus we have learned that balloons are in reality supported and pushed up by the surrounding air. Rainbows are distinguishable in certain ways from halos and the tints of soap-bubbles, although the colored bands are at first sight alike. Our fuller knowledge brings the direction of winds, and the varying length of day and night, into closer relation with the axis and the turning of the earth.

**8.** In a subject like Physics, the net gain from observation includes some notion of "how things work." What is presented as scientific knowledge will seek to offer a reasonable explanation of the way in which results are brought about. We do not allow that the full meaning of what is seen, heard, and felt has been interpreted, until we realize how it came to pass. Where the details are not visible, we must form some mental picture of the process, our minds helping themselves as best they may with analogies to things that are more tangible and can be seen. Finding that iron is heated by hammering, there is one natural suggestion (and it was followed formerly) that heat is squeezed out by the blow, like juice from a lemon. Again, as the common figure of speech puts it, "Air

absorbs moisture and becomes saturated." And, consistently with this, the process by which a puddle dries up, or dew is deposited, is paralleled with the image of a sponge, alternately soaking up water and squeezed dry. As a matter of fact, the figures of the lemon and the sponge have both been set aside, for reasons that are given in their proper place. Thus revision of the views held, and rewording of the working rules or principles, keep pace with the continued study of phenomena. Any analogy is discarded promptly, when facts become surely known that make it unsuitable. The elementary contents of this book are in the main definitely settled conclusions of long standing; it is not probable that such plain summaries of facts will need revision in order to harmonize them with new discoveries. But they should remind us that they are an enduring monument of the same candid spirit and method which are now active in the most advanced investigations of to-day. Something of that spirit in us should inspire honest and faithful work, while we retrace the steps of first discovery in class-room or laboratory. Hold in mind continually that each rule put forward as true, and each process conceived as real, must stand every comparison with ascertained facts, if it is to be accepted. The habit of making that sort of comparison for oneself is a good one to form. In modern days Physics has attained to the stage of accurate measurement, and of theory [1] stated in mathematical terms. But that does not relieve the science from its more modest task of containing all the facts in a simple and consistent plan of description. Unless we first know *what* happens, the question *how* it happens does not arise. Acquainting

[1] Look up the etymology of this word.

ourselves patiently with the facts in the case (phenomena) comes before constructing a perspective view of the facts (theory).

**9.** Since the facts are so fundamental and important, it is often an urgent matter that the appeal to them shall be made at once, in order to decide how a principle may be best expressed, or which of two views adapts itself more closely to the process that takes place. In similar circumstances, astronomers are often compelled to wait; for instance, until a "Total eclipse of the sun," or a "Transit of Venus," occurs in the ordinary course of events. But in Physics and other sciences it is also possible in several ways to study many phenomena at will. This can be illustrated here, without waiting for special knowledge:

(1) We may repeat results by producing artificially the important conditions upon which they are known to depend.

How would you make a prolonged study of the colors shown by soap-bubbles?

(2) We may vary the conditions according to some plan, with the object of discovering which of them are indispensable to a particular result.

If a violin-string is to sound a given note, can it still be tight or loose, thick or thin, long or short?

(3) We may put to the test of actual trial any expectation that we have formed about what will happen in new combinations.

If you can light a match at the "focus of a burning-glass," when facing the sun at an open window, can a similar match be lighted with the same glass, after the window has been closed?

The study of facts under circumstances that are to

some extent controlled is called experimenting. We are still observing phenomena; but for an **experiment** matters are so guided as to select what we want, instead of trusting to the spontaneous operations of nature for our material. An experiment has been well described as a "Question put to nature." But we get the answer in facts — not in words; and much depends upon a shrewd interpretation of the facts, if nature is to be cross-examined successfully. Physics is strongly an experimental science. It improves upon the impressions made by chance contacts with external objects, mainly by the greater deliberateness and better plan in its methods, which experiment makes possible. Therefore the experiments accompanying the text should receive their full share of attention; they will repay a faithful study of them.

# PROPERTIES OF SOLIDS, LIQUIDS, AND GASES

## CHAPTER I

### SOLID, LIQUID, AND GAS AS PHYSICAL STATES

**10.** One distinction that is commonly made among substances recognizes them as being, some solid, some liquid, and some gaseous. The type of a solid is found in pieces of rock, wood, ice, iron. Such liquids as water, kerosene, alcohol, turpentine, are in everyday use. The third class is represented by familiar examples like air, coal-gas. The geometrical ideas of volume (bulk) and figure (shape) are connected in our minds with individual portions of such substances, which are frequently spoken of as bodies, or objects. Considerations belonging to Physics are introduced, when we ask in how far particular materials retain their shape and volume. The classification as solid, liquid, or gas follows the lines determined by the answer to that question. A fragment of rock retains both volume and figure unless special means are applied, for example, to crush and consolidate it, or to heat and melt it, or to dissolve it. Water changes its shape with great freedom, and conforms finally to the containing surface with which it is in contact; but the alterations of its volume producible by heating and cooling, or by compression, escape

notice ordinarily. This effect of heating can be made visible without difficulty (Ex. 1); though the change of volume produced in water by compression is so small that the older attempts to discover it failed (Ref. 1). A definite portion of air, however, depends for both bulk and shape upon the confining boundary. If the vessel be enlarged, the air still fills it (Ex. 2).

The qualities characteristic of these three **physical states** in which substances occur are exhibited in the instances chosen. A **gas** has neither volume nor figure of its own. The volume of solids and liquids is largely self-determined, the variation due to external conditions being comparatively small. But a **liquid**, like a gas, flows or can be poured; they are both **fluids**. The typical **solid** is a substance whose shape is changed to a measurable extent only by distinct effort. It does not fall apart into drops; nor do separate portions unite freely, and obliterate any surfaces of division.

**11.** Though larger quantities of liquid show no preference for any special form, yet a drop of water or oil, hanging from a glass rod, assumes a definite shape; so does a drop of mercury lying on a plate. Such drops will quiver if slightly disturbed, and appear to possess a tendency to regain their form, as rubber does (Ex. 3). Again, many solid materials will go on changing shape beyond power of recovery, if strongly pulled, or violently compressed, especially when such action is kept up for a long time. In this sense, metal rods are made to flow through small openings, in the operation of drawing wire. With a hydrostatic press, a block of cold lead can be squeezed out into a length of pipe. Timbers in mines are slowly shortened and bent (without apparent break or splinter-

ing) by the weight of overlying rock and earth. These indications that the solid and the liquid state are not so sharply separated, after all, are confirmed from another side. Some liquids, like ether, alcohol, water, are **mobile**, that is, flow and splash readily; but glycerine and tar pour sluggishly. We call the latter **viscous**. Lavas, as they cool, may show viscosity to the extent of flowing only a few meters a day, and thus bridge part of the gap between water and lead.

Notice the behavior of pitch, asphaltum, paraffin-wax, putty, clay, and (cold) sealing-wax. Would you rate any of them as solids?

What proportions of gelatine and water yield a solid jelly?

**12.** The features of likeness within each group, and of difference between the groups, are prominent enough to make practically serviceable the subdivision into solids, liquids, and gases. But, as we see, it may nevertheless prove uncertain, in some particular case, to which class an actual substance should be assigned. It is not a question here of applying *definitions* like those of algebra and geometry. Between triangle and quadrilateral, or between equations of the first and the second degree, the distinction is sharp, and there are no stepping-stones. From solid to liquid, on the contrary, we find somewhat of transition. The boundary is blurred like the edge of a shadow in sunlight, because the properties that we rely on to establish the difference are more or less evident in various substances, and in the same substance under differing circumstances. Fortunately, it is not urgent to reach a logical decision in such doubtful cases. The matter of real importance is to realize why they present themselves.

There is no danger in leaving open the question as to whether a body is solid or liquid, when conditions are special or exaggerated.

Descriptive adjectives applying to solids are: hard, soft, ductile, malleable, brittle, flexible, friable. Make sure of their meanings, and under each word name one material that is typical of the property.

## THE POROUS STRUCTURE OF SUBSTANCES

**13.** It may next be asked whether solids, liquids, and gases fill completely the volumes that we are accustomed to say they occupy. The evidence as regards gases is direct and fairly conclusive. Into a space that contains air already, new portions of gas can be forced with any compression-pump, of which the bicycle pump is now a familiar form. What is true in this respect for the oxygen and nitrogen of air, is true also in the case of coal-gas, hydrogen, etc., that are prepared artificially. A considerable supply of oxygen, hydrogen, or coal-gas is now furnished commercially in portable form, by pumping it into a strong metal cylinder. The air-rifle, the dynamite gun, the caisson for excavation under water, and the diving bell are all furnished with compressed air (Ex. 4). This whole range of facts can be explained naturally by supposing that there are spaces among the particles of gas, in which added particles can be stowed away. And the same view is in harmony with the expansion of gases into enlarged volume. We can scarcely do otherwise than imagine the parts to be spread in open order — more and more as the volume pervaded becomes larger (see § 8).

**14.** The name **air-pump** indicates on its face a contrivance for pumping air either into or out of a confined space.

But in its prevailing use the word suggests rather a pump for removing air from a vessel. The mechanical arrangements of air-pumps differ, but they depend finally upon the expansive property of gases. The invention of the air-pump in its early form falls in the seventeenth century; a stirring period of experimental inquiry (Ref. 2).

The diagram (Fig. 1) shows the general plan of one type of air-pump. The piston *P* fits the cylinder *C* air-tight, and slides up and down; the vessel *R* from which air is to be removed is connected with *C* by a pipe. Communication between *R* and *C* can be shut off by a tap *T*; and another tap *S* governs the access of outer air to *C*. With *T* open, and *S* closed, raise the piston from the bottom of the cylinder. The air originally in *R* now divides itself between *R* and *C*. The piston being at its highest position, close *T* and open *S*; then, as *P* is pushed down, the air in *C* is forced out. By the repetition of these operations, parts of the air in *R* are successively got rid of, and a **partial vacuum** is produced in that vessel. The word "vacuum" implies emptiness; but we should be cautious about assuming that any space is made *completely* empty by the use of an air-pump.

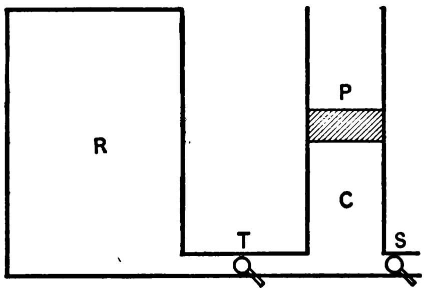


FIG. 1.

How could the same contrivance (Fig. 1) be employed to force air into *R*?

Examine an air-pump; also a bicycle pump; and see in

what ways the actual construction differs from the scheme shown in the diagram.

**15.** Turning next to liquids, there is a similar line of evidence from changes of volume that their parts may be caused to approach and to recede from each other, with the conclusion that interspaces exist between the particles. The compressibility of liquids can be made evident directly; but the readiest means of exhibiting their expansion and contraction has been referred to already (Ex. 1).

Confirmation of the general idea is to be had, also, from the behavior of some liquids on mixing them. Thus, if 50 c.c. of strong alcohol and 50 c.c. of water be poured together, the mixture is less than 100 c.c. in volume. A similar result follows on pouring strong sulphuric acid into water (Ex. 5). These consequences are accounted for, if the particles are more closely packed in the mixtures than in the original liquids.

It is further well known that solids and gases can be dissolved in liquids, and yield clear limpid solutions. Here, too, the bulk of the solution is often noticeably less than that represented in the materials separately (Ex.).

Name some instances of solution with which you are familiar.

**16.** As regards solids, there are gradations of fineness in open structure. The vacant spaces are visible to the naked eye in sponge and pumicestone; they show under the microscope in cases like hardwoods and the tissues of plants and animals. Water oozes through walls of unglazed baked clay; and it can be forced through lead, silver, and gold (Ref. 1). Mercury can be strained through buckskin. Gases resulting from the burning of coal in stoves and furnaces pass with some freedom

through plates of iron at a red heat. We can accumulate evidence of this nature that many solids are **porous**, applying the term "pore" to any interspace; either visible to the eye or with a microscope, or inferred from the passage of gases and liquids through solids. Where such evidence fails, we can fall back upon changes of volume. These are always producible directly by stretching and compressing, or more indirectly by heating and cooling (Ex. 6).

**17.** The facts for all three physical states being as we find them, it is natural to resort for interpretation of them to our contact with objects of larger size piled, or done up in packages, with visible open spaces. Since no facts contradictory of this simple view appear, we are at liberty to follow the lessons of larger experience and imagine the minute structure in this way (see § 8). How the open order comes about, and how it can be maintained permanently, are further questions, to be left unanswered here, at least. To many such questions the answers have not yet been made out; and where such is the case, we must accept even that situation with patience.

What we speak of as particles may be minute beyond all hope of observing them as individuals and measuring them directly. But the properties of some substances enable us to carry subdivision to a remarkable extent; and we can draw useful inferences about the possible sizes of particles. Thus gold-leaf can be prepared, less than 0.001 mm. in thickness, still showing all the properties of gold. Coherent films of gold and silver can be obtained by depositing them on glass, etc., with a thickness not exceeding 0.000001 mm. Bodies of measurable weight can be hung from fibres of silk and quartz that are invisible

to the naked eye. Consider, too, familiar examples like musk, and the intensely colored aniline dyes. The scent of the former causes no observable loss in weight during a long time. And 1 c.c. of alcohol colored with aniline continues to show the color after dilution with several liters of water.

# CHAPTER II

## WEIGHT, SPECIFIC WEIGHT, BUOYANCY

**18.** There is abundant evidence that solids and liquids, at least, are heavy. It is a matter of universal experience that they fall when unsupported, and that effort or contrivance of some kind is required in order to hold them up. And we are accustomed to trace these effects back to the earth, which is regarded as the source of an influence called **weight.** The share of this influence exerted upon a particular object is referred to as the weight of that object. We think of their weight as pulling liquid and solid substances down to the earth's surface; and farther down, if any channel like a well or mine-shaft is open; the general direction of the pull being toward the earth's centre. These notions have become so nearly instinctive with us that, when a body does not fall, we ask "Why?" and are led to examine in what manner its weight is resisted or overcome. It can be pointed out at once, for example, that we rely upon what is known as the "strength" of certain materials to support weight. Thus a lamp is hung from a ceiling by a chain; a book lies upon a table; a bridge is held up by its piers. But in every such case, what we name as the support is likely to be only the first of a series. For ceilings rest upon walls, whose foundations are sunk in the earth; tables stand upon floors, and so forth. The weight of the first object is handed on from

point to point along a line, until bearing is found upon the earth itself; there is something equivalent to a prop or wedge, holding the earth and the body apart.

**19**. One contrivance for setting off weight against weight, and thus preventing the approach of a body to the earth's centre, is of special interest because of its frequent use; this is the **equal-arm balance**, or **scales**. The scale-pans and stirrups, $S_1$, $S_2$ (Fig. 2), as well as the arms, $B_1$, $B_2$, of the beam, are made alike on both sides of the knife-edge $K$. If then the pull on a body $C$ in $S_2$ counterpoises that on another, $A$ in $S_1$, we conclude that these pulls are equal, since the balance itself is symmetrical, and favors neither $A$ nor $C$. This remains true, whether the two pulls are *entirely due to weight or not.*

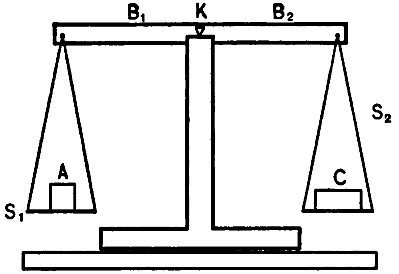



FIG. 2.

Observe whether a state of balance that exists is disturbed by interchanging $A$ and $C$, or by shifting each in its scale-pan.

Again, when logs float in water, their weight is neutralized by what we term the **buoyancy** of the water. Similarly, a steel ball can be buoyed up by mercury, and float in it. Further, the weight of an iron nail can be compensated with a magnet; an electrified glass rod keeps small pieces of paper from falling; oil moves up through a lamp-wick, instead of down (Ex. 7). Though all these methods of supporting weight are in a certain way familiar, there is, of course, much still to be learned about them

which the study of Physics may teach. The phrases, buoyancy of water, strength of brass, magnetic attraction of steel, etc., serve in the first place only to distinguish one type of action from another. But the words will be gradually enriched with meaning, if we study the phenomena patiently.

## WEIGHT OF GASES

**20.** Evidence for the weight of some gases is found in the fact that they fall in a stream unmistakably, like water, when poured out of a vessel (Ex. 8). On the other hand, a toy balloon or a soap-bubble, filled with coal-gas or hydrogen, will rise through the air of a room until stopped by the ceiling (Ex. 9). So it is not astonishing that weight was not attributed to air and other gases until that property was directly and conclusively shown in them (Ex. 10). The experiment just quoted is practically a repetition of Galileo's original proof that air is heavy (Ref. 3).

In the light of these results, it seems fair to conclude that gases are heavy substances, like liquids and solids, and to class the rising of a balloon among exhibitions of buoyancy, its weight being masked somehow by the surrounding atmosphere. Notice, as a parallel instance, that a marble falls, and a wooden ball of the same size rises, when held under water and released (Ex.).

## MEASUREMENT OF WEIGHT

**21.** The weight of different objects may often be compared readily as greater and less, by judging of the muscular effort needed to lift them. Or we may infer which

preponderates[1] from observed results like some of those in the two preceding sections. The closeness of muscular estimate is increased remarkably by practice, as in handling coins at a bank or mint. But it is desirable to measure physical quantities (among which weight is one) with a simple instrument that can be generally used, and to express them numerically as so many times a chosen unit or standard. By following this course with regard to weight, two advantages are secured: (1) the need of exceptional skill and training disappears; (2) the difficulty of making consistent judgments at long intervals is avoided. The equal-arm balance (Fig. 2, § 19) and the spring-balance (Fig. 3, § 24) fulfil the requirements; and we can measure weight with their aid.

**22.** The idea put forward in § 19 underlies this use of the scales. One scale-pan contains what is to be weighed, and the other a group of Weights,[2] the latter having been regulated by trial until the scales swing evenly, or are "balanced." The particular standards used in most laboratories to counterpoise objects on the equal-arm balance are marked as so many grams; that is, the **gram** is the unit of which they are multiples and sub-multiples. The original standard for the gram (from which our sets of Weights have been copied indirectly at several removes) is preserved carefully in the International Bureau of Weights and Measures at Sèvres, near Paris. The United States standards are in charge of the government office in Washington. The chief advantage to be recognized

[1] Look up the etymologies of this word and "counterpoise."

[2] As names for such standards the word will be capitalized, in order to set this sense apart from weight — the earth's influence (pull) upon bodies.

just now in the gram is that it belongs to the decimal metric system. Some other conveniences in its use will become apparent later (Ref. 4).

When the scales balance, the weights of the loads in the two scale-pans are taken to be equal, for ordinary purposes. So our thought attaches here to the *weight* of the standards; it is the weight of 10 grams, 50 grams, 0.5 of a gram, etc., that we have prominently in mind. On account of their present use they are called Weights. In order to save words, the "weight of one gram" will be spoken of as "one gram-weight" (1 gr.-wt.). So 10 gr.-wt., 50 gr.-wt., 0.5 gr.-wt. Let now a piece of lead be counterpoised by a group of standard Weights stamped as follows: 100 grams, 50 grams, 5 grams, 1 gram, 2 decigrams. Then the weight of the lead is measured as equal to the weight of 156.2 grams, or to 156.2 gr.-wt. More briefly expressed, the weight of the lead is 156.2 gr.-wt., or the lead weighs 156.2 gr.-wt., or there are 156.2 gr.-wt. of lead.

If the Weights are marked as pounds and ounces, according to the usage of our everyday life, the only changes necessary are to substitute pound-weight (lb.-wt.) and ounce-weight (oz.-wt.) for gram-weight above.

**23.** Note. — It must be admitted as possible that weights actually differ, though they seem equal in our measurement of them. The working conditions of experiment are not ideal. Scale-pans and arms are not exactly alike on both sides of the knife-edge; the moving parts do not turn with complete freedom, and differences in weight below a certain amount are not indicated. Even supposing that the mechanical construction could be perfect, there is air buoyancy to be reckoned with. We must not assume: (1) that its effects are confined to the few special cases spoken of already; nor (2) that they are equal on both sides of the scales and cancel each other (Ex. 11).

However, none of those elements need enter into our first thought about measuring weight. They modify the result by only a small fraction of itself, unless the circumstances are exceptional. In these beginnings, read the balanced scales as equal weights, without confusing the main idea with "corrections." The same policy will be pursued elsewhere; we shall emphasize most strongly the central thought and its consequences. The corrections necessary in measurements of the greatest precision tax the knowledge and the resource of expert workers in Physics; but their place is in the background until a firm grasp on the leading ideas has been obtained.

**24.** In the spring-balance, as usually constructed, weight is neutralized by the effort of a spiral spring to regain its "natural" length, when stretched or shortened. In some forms for commercial purposes, the spring is shortened in use; but it is, perhaps, more commonly lengthened. The latter case alone is taken up here, since the same ideas can be applied easily to both forms. The numbered scale over which the pointer or index moves (Fig. 3) can be graduated by means of known Weights. The starting-point (zero) being established by letting the balance hang free and unloaded, the mark "10" is read as 10 gr.-wt., if it is the position of the index when 10 grams hang at rest by the spring. At the marks 20, 50, 100 we read 20 gr.-wt., 50 gr.-wt., 100 gr.-wt., and so forth. Ascertaining the values in weight of the divisions on the scale is called **calibrating** the balance. The operation of calibrating can be quickened by noting the simple relation between the loads applied and the extensions produced by them which is apt to be fulfilled (Ex. 12).

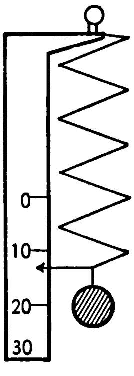


Fig. 3.

When a spring has been once calibrated, the result is

applied practically in measuring unknown weights. This use of it assumes that the spring is not permanently deformed by stretching, but returns always to the same length with equal loads. Recall the note, § 23, in connection with this instance. Do you detect that it has any bearing here?

The range of application for spring-balances is widened by constructing some with "stiffer" springs, and some with "weaker" ones. Contrast, for example, such balances used in stores, with the "Jolly" balance of the laboratory. How would you compare numerically the stiffness of different springs?

## FORCE

**25.** By this process of measuring it, the action of the spring is compared with weight. The spring-pull and the earth's influence are classed together as physical quantities, in so far as they produce effects of the same kind, and are measured in terms of the same unit (here the gram-weight). When they offset each other, there is a sort of physical subtraction; in other circumstances, such a pull or push may conspire directly with weight, and in that sense be added (physically) to it. In algebra, $a = -b$, and $b = -a$, follow from $a + b = 0$. Just so in Physics, the zero result of weight ($a$) and spring-action ($b$) combined, brings out that they are equal and similar magnitudes; their opposite directions are indicated by contrary signs. All physical effects that are measurable in grams-weight are grouped together under the name **force**. When we meet other forces, we shall find them, like weight and spring-action, causing, preventing, or controlling the motions of bodies.

## SPECIFIC WEIGHT

**26.** Equal volumes of different materials are not equally heavy. Without special measurement, a brick is felt to be heavier than an equal-sized block of wood, and lighter than one of iron or lead. But the remarks at the close of § 21 apply to these circumstances also; we cannot rest content with estimates of sensation, because they are not altogether reliable. Many questions arise in Physics that call for a comparison of weights in equal volumes which is definite and measured. In order to carry out this idea, one substance is adopted as a standard, and we determine by actual weighing how many times heavier or lighter than the standard substance any other substance or object is, when equal volumes are taken. On this basis of equal volumes, let the weight of substance $A$ be $W_1$, and of substance $B$ be $W_2$. Then the comparative weight of equal volumes is shown in the ratio $\frac{W_2}{W_1}$, and the value of that quotient is known as the **specific weight**[1] of $B$, *referred to A as a standard.* The commonest standard for the specific weight of solids and liquids is water; mainly because water of sufficient purity can generally be obtained on the spot where the necessary weighings are to be made. But air and hydrogen are also adopted at times as standards

[1] NOTE for the teacher. — The word "gravity," which is current in several connections as a synonym for "weight," is nowhere employed in the text. Alternative names for the same quantity are confusing — especially to beginners; and of these two weight seems the better choice. Gravity suggests strongly *gravitation*, between which and weight a clear distinction is to be maintained, of course, by more advanced students. The term "specific weight" conforms exactly to the model of the French and German equivalents (poids spécifique; specifisches Gewicht). "Specific density" would be premature, for the sequence of ideas here followed.

for the specific weight of gases. It shall be understood hereafter that comparison is made with water, where the standard is not explicitly mentioned. The table gives

APPROXIMATE SPECIFIC WEIGHTS

(Water as Standard)

| | | | |
|---|---|---|---|
| Aluminum | 2.6 | Zinc | 7.1 |
| Brass | 8.4 | | |
| Copper | 8.8 | Alcohol (95 %) | 0.82 |
| Crown glass | 2.5 | Ammonia (solution) | 0.90 |
| Flint glass | 3.5 | Chloroform | 1.50 |
| German silver | 8.5 | Copper sulphate (solution) | 1.16 |
| Gold | 19.3 | Ether | 0.73 |
| Iron, Steel | 7.5 to 7.8 | Glycerine | 1.27 |
| | | Sulphuric acid (15 %) | 1.10 |
| Ivory | 1.9 | Air | 0.0013 |
| Lead | 11.3 | Carbon dioxide | 0.002 |
| Mercury | 13.5 | Coal-gas | 0.0008 |
| Platinum | 21.5 | Hydrogen | 0.00009 |
| Silver | 10.4 | Nitrogen | 0.0012 |
| Stone (building) | 2.7 | Oxygen | 0.0014 |

some specific weights that may prove useful, but makes no attempt at close accuracy. The values indeed vary somewhat in different samples of commercial materials; so that results of laboratory work are to be preferred, where they are available.

The word "specific," here and elsewhere, denotes that comparison is made of the same quality in two bodies or materials, one being taken as a standard. One substance is specifically lighter or heavier than another, according as the specific weight of the first is less or greater than that of the second.

**27.** One experimental method of finding specific weight in a particular case yields directly the weights of volumes that are known to be equal, but are not measured (Ex. 13). In using this method, we are called upon to distinguish between two types of cases: —

(1) The specific weight found applies to the body as a whole, but not to every part of it separately. Thus a corked bottle containing a bullet, a marble, and a piece of coal may as a whole have a specific weight less than one (Ex.). But the bullet, the marble, the coal, and the (uncorked) bottle separately would show specific weights ranging from 2 to 11. In such instances, it is an average specific weight that is measured.

(2) The specific weight found applies to all the parts into which the body can be subdivided. For example, only minute differences exist among the specific weights of pieces cut from the same brass rod. In proportion as a body is thus alike in all its parts, it is called **homogeneous**. Our measurements then yield the specific weight of the material or substance, and the result is not limited to any particular piece or groups of pieces. Liquids have usually been rendered homogeneous by stirring, before their specific weights are determined. Non-homogeneous combinations of solid bodies are more frequent in practice.

When each of two materials ($A$ and $B$) is homogeneous, the specific weight of $A$ referred to $B$ as standard can be calculated, after weighing *known* volumes of $A$ and $B$ that are not equal. How is this done?

The numbers in the table (§ 26) are specific weights referred to water. How must they be revised, if mercury is chosen as the standard substance?

What simple relation do you find approximately real-

ized, between the weight of a portion of water in grams-weight, and its volume in cubic centimeters? Does this simplify the determination of specific weight, for the water standard?

## BUOYANT FORCE

**28.** When a stone hanging by a string is immersed in water, the effort required to keep it from falling is less in magnitude than its weight. According to the popular phrase, "A stone *loses weight* in water"; that is, the weight is in part compensated. Taking other pairs of solids and liquids, the former either sink with effectively reduced weight; or float at the surface, partly immersed; or just "lose" their entire weight, when submerged (Ex. 14). All these modifications are due to buoyancy (§ 19, § 20), of which we are now in a position to gain a fuller understanding. And the better insight is, as usual, connected with measurement of consequences. Wherever the weight of an object is thus neutralized in whole or in part, the buoyancy is measured as the number of grams-weight by which the weight is apparently diminished. According to the test mentioned in § 25, therefore, we rank buoyancy with the strength of materials (and other methods of supporting weight) as means of supplying force, and speak of **buoyant force.**

Cite at least two instances where buoyant force exceeds weight. By how much is weight apparently *diminished*, under such conditions?

## BUOYANCY IN LIQUIDS

**29.** The first important clew to the magnitude of buoyant force was furnished, for the case of solid immersed in liquid, by Archimedes (Ref. 5), and his name is still

linked with the principle applying to those circumstances. A plausible and simple line of reasoning that leads to his conclusion is given below ; yet it is better to confirm the result by direct experiment (Ex. 15). For danger lurks in the habit of relying upon bare argument, unsupported by facts of observation or experiment, even where we are only restating known physical truths.

Let the vessel, $C$ (Fig. 4), contain any homogeneous liquid, whose surface is shown at $DE$, the vessel and its contents being at rest. Consider any portion of the liquid, such as that indicated by the closed outline and marked $A$. Its weight is, as a fact, neutralized by the surrounding parts $B$ of the liquid. Now, we may ask, why should these effects of $B$ depend upon what substance is in $A$,—water, or lead, or glass, or iron? There is no *reason apparent* why they should ; and to that extent the argument is plausible, that the buoyant force must be as we find it. Experiment clinches the matter, by showing that the effects in question *are* the same, whatever object occupies the region $A$. The buoyant force of $B$ (liquid at rest) upon $A$ (any object submerged in it) is equal in magnitude to the weight of the liquid $B$ that would occupy the volume of $A$.

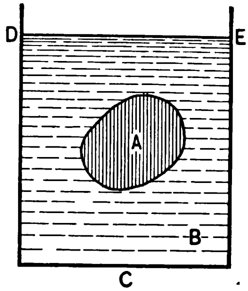


FIG. 4.

Does $A$ need to be homogeneous? Does $B$?

**30.** If the buoyancy is less than the weight of $A$, that body will sink unless otherwise supported. But the buoyant force may be the greater magnitude ; and in that case the body $A$ will rise unless held down, the greater force

prevailing over the less. At the boundary between these two conditions, there is equality of buoyant force and weight; its weight being just compensated, *A* has no tendency either to rise or to sink (see § 25), when entirely immersed and at rest. Where the upward force for the position of *A* in Fig. 4 is greater, and is allowed to prevail, the body finally floats as shown in Fig. 5. The buoyancy then depends upon the submerged volume of *A*, below the surface *DE*. The weight of that volume of the liquid *B* is equal to the weight of the entire body *A*. The same idea as to submerged volume and buoyancy applies, of course, if *A* does not float in the position of Fig. 5, but needs to be held; either held up, or held down.

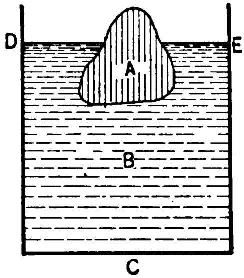


Fig. 5.

The way is now prepared to understand and accept the **Principle of Archimedes**, for the range covered by the following statement: The buoyant force acting upon a body that is immersed (wholly or partly) in a homogeneous liquid is equal in magnitude to the weight of that liquid whose place the body takes.

In what respect is it easier to swim in the ocean than in fresh water? What change in the load line would you expect, when a vessel passes down the St. Lawrence River to the Atlantic Ocean? [The specific weight of ocean water is 1.02.]

## METHODS OF FINDING SPECIFIC WEIGHT

**31.** In expressing the conditions of floating and sinking, the principle of Archimedes brings into comparison

the weight of equal volumes for liquid and solid. And this establishes in several ways practical relations with the idea of specific weight. First, when the specific weights of both solid and liquid are known, it is possible to foretell whether the former will float or sink in the latter.

State the rule in your own words. Does it apply to both cases of § 27, or to one only?

Secondly, the measurement of buoyant force, in special cases of a solid insoluble in a liquid, is one step in a convenient method of determining specific weight (Ex. 16), because we find thus the weight of so much of the liquid used, as is equal in volume to the (totally) immersed solid. Denote this by $W_1$; if in addition the weight $W_2$ of the solid is known, its specific weight, referred to that liquid as standard, is $\frac{W_2}{W_1}$.

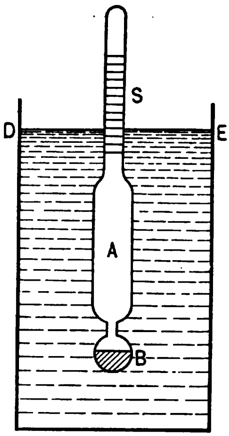


FIG. 6.

Show how reference can be transferred to the water standard.

Explain in detail how the final ratio (specific weight) is obtained in all three variations of Experiment 16.

Thirdly, the relation between weight and buoyancy for *floating* bodies is utilized in measuring the specific weight of liquids and solids. The instrument represented in one form by Fig. 6 is known as a **hydrometer.** Being ballasted with mercury or shot in the lower bulb, it floats steady in an upright position. With different liquids, their surface *DE* cuts the scale *S* at different marks. The scale having

been calibrated previously by using liquids of known specific weight, the scale reading at *DE* gives immediately the specific weight of any liquid in which the instrument floats (Ex. 17).

The next diagram (Fig. 7) shows a contrivance known as **Nicholson's hydrometer**. In use, this hydrometer floats steadily, with the surface *DE* always cutting the stem *S* at the *same* index-mark. This is brought about by regulating the Weights *C* on the upper platform *P* (Ex. 18). In finding the specific weight of a solid, the instrument is first adjusted in water with the object on *P*, and then the Weights are noted that must be added there to restore adjustment, after shifting the object from *P* to the submerged platform $P_1$.

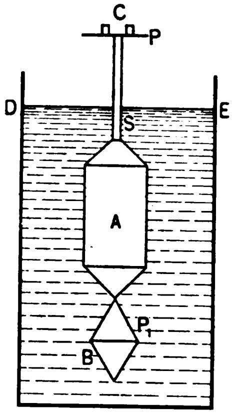



Fig. 7.

If *a* grams are thus added, what does *a* gr.-wt. measure? What else is needed, in order to calculate the required specific weight? Can you determine this element with the hydrometer itself and a set of Weights?

How can the instrument be employed in determining the specific weight of a liquid?

## THE PRINCIPLE OF ARCHIMEDES FOR FLUIDS

**32.** The principle of Archimedes, in the form proposed at the end of § 30, though limited to immersion in liquids, gives a plain lead toward the consideration of buoyancy due to air and other gases, of which a glimpse is offered

in § 20. First, the argument connected with Fig. 4 (§ 29) extends unweakened to the circumstances of any object surrounded by an atmosphere of gas (both being at rest). If that gas should replace the object, the weight of the former would be neutralized by an upward force. The buoyancy is this upward force (so the logic runs) unchanged in magnitude by mere substitution of other material for the gas.

Secondly, Experiments 8, 9, 10, 11 throw light upon the matter in question. Buoyant force is shown to occur in gases (Ex. 11). For certain instances, the fact is exhibited that buoyancy is greater or less than weight, according as the specific weight of "atmosphere" is greater or less than that of object (Ex. 8 and Ex. 9, compared with the weighings of Ex. 10). These results complete the reasonable requirements as to experimental evidence, except that they leave *unmeasured* the *equality* of the buoyant force and the weight of displaced gas. That parallel to Experiment 15 can be furnished; but it involves more delicate weighing than we are now prepared to make. The result of such weighings, when they are made, confirms the suggestions of the above experiments and reasoning. Let us accept that result. Then adding this evidence to what we have already, there is adequate ground for announcing the following rule, whose scope is wider than that of § 30: —

The buoyant force acting upon a body that is immersed (wholly or partly) in a fluid is equal in magnitude to the weight of that fluid whose place the body takes.

This extension of the principle concerned with buoyancy exhibits another important property common to both liquids and gases.

**33.** The general idea including all instances of buoyancy can be stated otherwise: Wherever there is competition for a lower position between two substances or objects, and they are *free to move*, the one which is (on the whole) specifically heavier carries the day. The other is forced up, its weight being overcome (Ex. 19). The words within parentheses cover cases like the floating of iron ships, or an eggshell ballasted with shot (see § 27 (1)).

Discuss the rising of gas-bubbles through a liquid like water; through glycerine; also Experiment 19.

In which of these sections do you find the explanation of the layers formed in a vessel by liquids that do not mix (Ex.)?

We have been supposing that no other forces interfere with the results, and studying the consequences of the comparative magnitudes of buoyancy and weight. Why do shot and sawdust in the same box not arrange themselves in layers, like water and kerosene? What property of mobile liquids is indicated by this difference between them and powdered solids? In what way does the viscosity of liquids affect the phenomena?

The specific weight of air in a closed space can be varied by forming a partial vacuum there, or by pumping more air in. The value in the table of § 26 is a fair average for the conditions in a room, or in the open air. Using that value, estimate the percentage error of weights measured in air under the following circumstances: —

(1) A wooden block (sp. wt. = 0.5; volume = 800 c.c.) weighed on a spring-balance that has been calibrated in air by using brass Weights (see § 24).

(2) The same block counterpoised with brass Weights on an equal-arm balance.

(3) A solid brass block of any size is substituted for the wooden block in (2).

(4) The weight of a pure gold nugget is measured as 100 gr.-wt. on an equal-arm balance, when counterpoised with brass Weights.

Is the (true) weight greater or less than the measured weight in (2) and (4)? Under ordinary conditions of weighing, is a "pound of feathers" heavier or lighter than a "pound of lead"?

Can the effects of air buoyancy be neglected in such weighings as you are called upon to make (see § 23)?

# CHAPTER III

## PRESSURE. CHANGE OF VOLUME

**34.** Some instances have been presented in Chapter II, where one force compensates another, so that motion does not occur as it would if either force prevailed, or acted alone. What is found true of weight and buoyancy when a body floats — that they just offset each other — is observable also with other influences measured in grams-weight. Thus two spring-balances can be attached to a block of wood and pulled in opposite directions, yet the block may remain at rest. Everyday life is full of further examples, in which a body is pushed or pulled from several sides, but left at rest nevertheless. Such pairs or sets of forces neutralize one another so far as producing motion is concerned; it cannot be said, however, that they nullify each other in all respects. That is, though the body does not move, its condition is not the same as if none of the influences was affecting it. Under such circumstances, a spring is lengthened, shortened, bent, or twisted; rods may "buckle" or break; lead and other metals may be squeezed out of shape between the jaws of a vise; glass, and other brittle materials, may snap or splinter. The use of nut-crackers, scissors, and many tools depends upon the consequences of equal opposed forces.

Now it is easy to recognize that the internal state of

bodies is affected, before visible breaking or cutting is produced. A certain demand is made upon the strength of the particular material, to resist the separation or the crowding together of its parts; or the sliding of one layer past its neighbors in bending and twisting. We can see that a spring yields visibly under the demand, but the yielding is less in proportion as the spring is stiffer. And even a steel bridge sags by a measurable amount under the weight of a passing train which it supports. These forms of internal resistance to deformation must be accepted (for our present purpose, at least) as given and unexplained properties of the substances with which we deal. While it is sometimes convenient to rename the resistances of this type as "rigidity," "cohesion," "molecular forces," etc., the situation is not changed by doing that; for it must not be supposed that the mere use of new words lessens our ignorance, affords further insight into the facts, or supplies additional explanation of them.

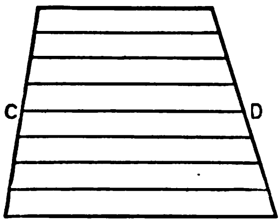
## TRANSMISSION OF FORCE

**35.** The scope or range of these internal resistances is not the same for all three physical states, being narrower for liquids than for solids. As a result of some peculiar internal structure, to be inferred from the phenomena, solids are braced more or less vigorously against external effort to modify their shape, as well as their volume. The typical fluid, on the contrary, permits rearrangement of its parts, — for example, in stirring, — and offers *effective* opposition to change of volume alone. Sluggishness in flowing, observed with viscous liquids, retards the rearrangements without finally preventing them.

As a consequence of rigidity in various forms, a solid moves as a whole, all parts together. Any effort toward displacing it, made by pushing or pulling at its surface in one place, is felt and must be counteracted elsewhere, if the body is to be held at rest. In this plain sense, solids are said to **transmit force**. The rope used at a "tug-of-war," for instance, gathers into itself and transmits the united pull of either team, to be balanced by the united pull of the other. The squeezing action of a vise or press of any kind results from meeting and opposing on one side the push originating on the other, and handed on through the body itself.

**36.** It is not a hard matter to form some general notion about the internal condition of a solid, while its strength or rigidity is being put to the test by bending, twisting, stretching, or compressing it. But the exacter knowledge of the phenomena in detail is complicated with difficulties of fine measurement, and of mathematical expression. Beyond the first stage of which we have been speaking, therefore, where the phenomena are familiar and even obtrusive, the discussion of "strength of materials" lies on the whole outside the limits of our present plan. We shall not enter upon it, although it is a field of greatest importance and interest to the constructing engineer. On the other hand, the internal condition of liquids and gases, when held at rest by balanced forces, is such that several leading principles, which apply to them and are connected with everyday affairs, can be established on a basis of simple experiment. Those principles are introduced in the sections that follow. Their wide range of application to so many kinds of liquid and gas points to certain features of simplicity in structure, common to all fluids.

**37.** Suppose that any liquid is standing in an open vessel. Then the weight of the liquid is supported; and, when it has been poured into a flask or dish of any form, a liquid adds neither more nor less than its own weight to the downward force felt, on the whole, upon the vessel (Ex. 20). It is equally true, if a solid material like wood is piled in horizontal layers upon a table, that just the entire weight is transmitted to the support. There is no difference between solid and liquid in this respect. But further, at any joint of the solid pile, like *CD* (Fig. 8), the summed-up weight of the layers above the joint is

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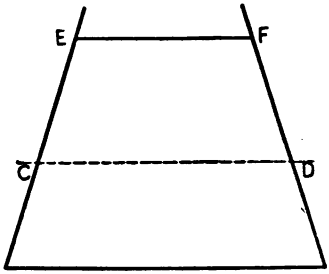


FIG. 9.

felt; this much of force is transmitted to that bearing-surface as the effect of weight, and distributed over its area. We ask, now, concerning any open vessel filled with homogeneous liquid to the level *EF* (Fig. 9), is the entire downward force, caused at any plane *CD* by the weight of the portion *CDEF*, just equal to that weight? The plane *CD* may be thought of here as replacing the joint *CD* (Fig. 8), and forming the boundary between the liquid above it and below.

We shall examine carefully the experimental answer to this question.

**38.** The indication is that the force acting down upon equal horizontal areas has equal values at all places within the liquid that lie in one horizontal plane (Ex. 21). This result includes the (horizontal) surface of contact with the air; the **free surface**, as it is called. And the rule is found to hold, whatever form be given to the vessel, provided that it contains only one *connected* body of liquid. Thus a horizontal section of the liquid may be made up of detached areas, as shown at 1, 2, 3 in the diagram (Fig. 10). The free surface also consists of three parts, *AB*, *CD*, *EF*. But there is connection through the liquid in the region *GH*, and the rule applies.

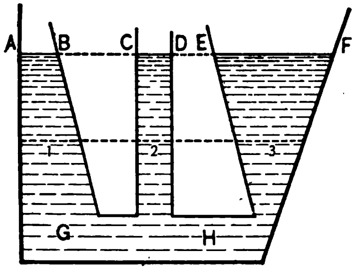


Fig. 10.

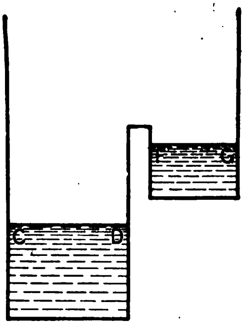


Fig. 11.

Would you extend the rule to the case represented in Fig. 11? The vessel has two compartments, in which the free surfaces are *CD*, *FG*. Can this case be made like that of Fig. 10 by pouring in more liquid?

What instances does your experience supply, where water "stands at the same level" in vessels of unequal size, in which there is free communication for it between them?

What lesson does the (calm) ocean teach about the real form of the free surface, or level surface, for water, which we treat as a plane in small vessels?

## VERTICAL PRESSURE IN LIQUIDS

**39.** In comparing conditions at different levels in the same vessel, or in different vessels, equal areas are to be taken. It is convenient for numerical work to fix upon one square centimeter ( 1 □ cm.) as the standard for such purposes, because it is the unit for measuring areas, and to specify the force exerted against that. This value would be common to each square centimeter of area at a given level, under the conditions of Experiment 21. The force that falls to the share of 1 □ cm. of a surface, and is perpendicular to it, is called the **pressure** in the direction of the perpendicular, or the pressure upon the surface, at the place where that square centimeter is chosen. For a horizontal surface in a liquid at rest, then, the pressure is the same at all parts, and the entire force acting downward upon the surface is found by multiplying the pressure upon it at any place by the number of square centimeters in the total area. Call that number $N$; let $P$ be the value of the pressure anywhere at that level; then, if $F$ is the entire force for the whole area,

$$F = P \times N. \qquad (1)$$

**40.** If the testing area is placed (still horizontal) at a greater depth, the force acting against it is increased (Ex. 22). When corresponding changes in depth and in force are determined by measurement, the following relation can be made out: With each added centimeter of depth

below the free surface, the increase of downward pressure is equal to the weight of one cubic centimeter of the (homogeneous) liquid.

Show in detail how your experimental work leads up to the conclusion stated above.

What is the weight of 1 c.c. of a substance whose specific weight is $s$?

According to the rule that we have now obtained, the pressure downward would not change on passing from one horizontal layer to another, if one cubic centimeter of the liquid weighed *nothing;* that is, if the liquid were not heavy. Put into other words, this means that any downward pressure applied at the upper surface would then be handed on unchanged. But that action of the liquid is not prevented nor interfered with when weight comes in; the downward pressure is still transmitted toward the bottom of the vessel from the top without alteration, except that now each layer *also* contributes by the way an increase of pressure due to its own weight. Thus a greater pressure is gradually accumulated for transmission to the lower layers.

**41.** At the free surface in an open vessel, there is actually pressure downward upon the liquid to begin with — atmospheric pressure (Ex. 23); this cannot be avoided unless special precautions are taken. So following out the thought of the last section, we are able to see two parts in the pressure felt and measured at any level; one is the atmospheric pressure just passed along downward from the free surface, where it is applied, and the second is caused by the weight of the liquid itself. Let $P$ stand for the vertical pressure really experienced, $P_A$ for atmospheric pressure, and $P_W$ for pressure due to the

weight of the liquid. Then the relation expressed in symbols is

$$P = P_A + P_W. \tag{2}$$

The atmospheric pressure on the waters of the ocean is not far from 1000 gr.-wt. [Remember that *pressure* is the quota of force acting on *one square centimeter* of surface.] The water being 10 meters deep over a level rock 2 meters square at the bottom of a bay, how many grams-weight of force does the rock withstand (see § 30, questions at end)?

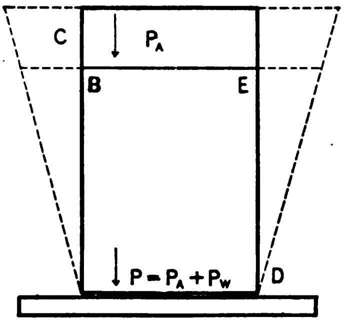


FIG. 12.

Develop this idea into a more general problem. Let $P_A$ be the air pressure (any value; *e.g.* in a partial vacuum, or after compression) in a closed cylindrical vessel *CD* (Fig. 12), standing on a level base containing *a* □ cm., and filled to the line *BE* with liquid of specific weight *s*. The number of centimeters in *ED* is *n*. What total downward force does the liquid exert upon the bottom of the cylinder?

Would this result as regards the base be changed if the vessel were a cone of section shown by the dotted lines, other conditions remaining unaltered? In the conical vessel, $P_W \times a$ is

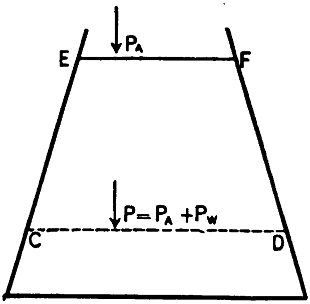


FIG. 13.

less than the weight of the liquid; where is the rest of that weight supported?

The conical vessel *ED* (Fig. 13) stands on a level base, and is filled to the line *EF* with liquid, 1 c.c. of which weighs *w* gr.-wt. Show for any level *CD* that the force downward *due to the weight of the liquid* is greater than the weight of the portion above that level.

What answer can now be given to the main question of § 37?

## LIQUID PRESSURE IN ANY DIRECTION

**42.** A third consequence of experiment is next to be introduced, which throws still more light upon the internal condition of liquids. The result indicated through the rubber diaphragm (Ex. 24) does not change when the testing area is turned into a vertical or an inclined position, so long as its centre is kept at the same level. This means that the total force acting perpendicularly to a small circular area remains the same in all such positions. As the circle is turned, one part may go deeper, the force against it increasing; but another equal part is brought nearer the surface, and the corresponding force is diminished. On the whole, loss and gain offset each other. In an inclined or vertical position, it is no longer true that the force exerted upon one square centimeter has the same value everywhere in the circle; that is, the *pressure is not uniform* all over the area of the circle. But it is still possible to express the condition of affairs in terms of an **average pressure** for the whole area. We must first explain, however, the meaning of "average" for its present use, and for many other cases that occur in Physics.

**43.** The interpretation to be attached here to the idea contained in average may be brought out most readily from two or three familiar illustrations. If we divide the total population of a State by the number of square miles in it, the quotient gives what we call the average of "population to the square mile." Consequently, if we multiply that average by the number of square miles, the product gives again the actual population. Let $P$ stand for (total) population, $N$ for the number of square miles, and $A$ for the average. Then, because $A = \frac{P}{N}$,

$$P = A \times N. \tag{3}$$

This equation does not mean that $A$ people are actually located upon each square mile (nor upon *any* square mile, even), but it shows that if the number of people was *uniformly* $A$ upon every square mile throughout the State, the total population would foot up exactly as it does in reality.

Similarly, if $N$ is the number of acres planted with wheat in Minnesota, from which the crop is $B$ bushels, the average yield to the acre is $\frac{B}{N}$. Then if there were a uniform yield of $A\left(=\frac{B}{N}\right)$ bushels on every acre, the total crop according to that supposition would be equal to the one actually harvested. For later applications of these ideas it is useful to notice that any such main average is itself made up from averages taken within smaller ranges. Thus, if the average yield is $A_1$ bushels to the acre for one county of $N_1$ acres, $A_2$ bushels for another of $N_2$ acres, and so forth, including all the counties, we should have

$$B = A_1N_1 + A_2N_2 + A_3N_3 + \text{etc.} = AN,$$

and
$$A = \frac{A_1N_1 + A_2N_2 + A_3N_3 + \text{etc.}}{N}.$$

Again, if the distance between two cities is $D$ miles, and the number of hours in which the run is made by a train is $N$, $\frac{D}{N}$ represents how many miles an hour a train must travel uniformly or steadily, in order to cover the same distance in the same time; $\frac{D}{N}$ is the average speed. And in many familiar cases like this, calculating an average can be viewed as determining a value which, if it prevailed uniformly within certain limits of space, time, etc., would give the same aggregate *for the whole range* that is in fact observed.

When we say that the area of a triangle is equal to the product of its base by half its altitude, we are really connecting the triangle with a rectangle on the same base. The constant altitude of the rectangle at all parts of the base is the average altitude in the triangle.

Returning to § 27, (1), how can the average specific weight there spoken of be interpreted as the specific weight of a homogeneous body?

**44.** The application of these thoughts to average pressure ought now to be plain. If a total of force, $F$ gr.-wt., is distributed *on any plan* over a surface of $N$ □ cm. to which it is perpendicular, the average pressure for the surface is $\frac{F}{N}$. It is well to distinguish an average value from one that is really uniform by placing a dash ($\overline{\phantom{x}}$) over the former. So we write

$$\frac{F}{N} = \overline{P}; \qquad F = \overline{P} \times N. \tag{4}$$

Point out the difference between the second form of (4) and Equation (1) (§ 39). In what position of the circular diaphragm is the pressure practically uniform, and equal to the average pressure for other positions?

Since the average pressure for a small circular area does not differ noticeably from the pressure on the square centimeter immediately round its centre, the average value is often referred to as the pressure at the centre (of the circle). In this sense we speak of the **pressure at a point,** as a short expression for "average pressure on a small circle described round that point as centre." Making use of this idea, the principle derived from the discussion of § 42 can be announced in these words: The pressures due to the combined effects of atmospheric pressure and weight of liquid are equal for all directions at one point in the liquid.

PRESSURE DUE TO MOBILITY OF LIQUIDS

**45.** The equality of pressures in all directions at any point is so important a property of liquids that it will repay us to look farther for a definite reason why a liquid behaves in this way. Take first a vertical column of liquid such as *AB* (Fig. 14), reaching from the free surface *CD* to a level *B* in an open vessel of any form. In this case, the rules of § 40 and § 44 formulate no more, as regards *vertical* pressure (up or down), than the plain fact that additional weight is felt, and is supported, at the

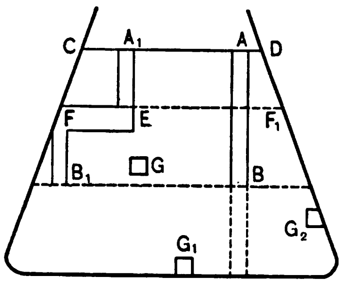


FIG. 14.

base *B*, when the column is lengthened downward by one centimeter. On each unit area (1 □ cm.) of that base there is added the weight of unit volume (1 c.c.); and an equal upward pressure is called out to balance this. We should meet the same situation in a column of wood (see Fig. 8, § 37); the essential difference between a column of water and one of wood is that the former would *crumble* under its weight, unless supported on all sides as well as below. Because of its internal structure or rigidity, wood is not crushed outward at the sides by its weight. But sawdust has lost that kind of structure; so has rock, when disintegrated by weathering. Sand and sawdust slip down into a pile, instead of standing alone as a block. It is true that they do not spread out into a thin sheet as water would. The particles of powdered solids do not slide with complete freedom; sand, for instance, will retain a definite slope, depending upon a remnant of friction among the grains (see § 33, shot and sawdust).

The extreme case of crumbling, when the parts slide over each other without appreciable *permanent* resistance (see § 35), is met when liquids under the influence of outside pressure and weight press sidewise; and in fact outward in all oblique directions; just as strongly as they press downward (or upward). Within the liquid, the particles are squeezed between the heavy layers above and the walls of the vessel below. At the same time any pressure from the outside, like atmospheric pressure at the free surface, is carried on and felt at each layer until the solid wall of the vessel "takes it up." This evidently adds to the squeezing action on the liquid. Being forced together in that way, the slippery particles will escape in every direction laterally, unless restrained with even

inward pressure on all sides. A force applied anywhere to a liquid must be counteracted *everywhere;* while it can be balanced by one force at a definite place if applied to a solid (see § 35). And when the particles are held finally, it is because the side-walls of the vessel do not give way; the resistance of these at every point is equivalent to an *inward* pressure upon the contained liquid, which is paired off with the effort of the latter to fall and to spread. The impossibility of doing either follows from the equal balance of the force upward and downward, to right and to left, and so forth, upon every particle.

**46**. Any small cubical block of liquid, $G$ (Fig. 14), presses outward at each face against its neighbors, which meet it everywhere with equal inward pressure, just as the walls themselves press inward upon blocks like $G_1$ and $G_2$, at the faces adjacent to them. The situation, so far as the block $G$ is concerned, is somewhat like being held in three vises at once, one for each pair of parallel faces. Select two of these vise-actions, and note that they are passive, preventing the liquid from evading a third active squeeze by slipping out in a direction of weaker pressure. In this sense, for the case in question, atmospheric pressure and weight are the active causes, and the horizontal pressures are consequences.

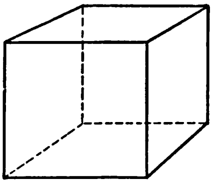
FIG. 15.

Take the diagram (Fig. 15) representing the block $G$ more completely, and indicate by arrows the directions of the forces exerted *by* the neighboring liquid *upon* each horizontal and vertical face of the block. On which pair of faces are the pressures *uniform?* Are the pressures on each of this pair *equal?* Are the average

pressures on the four other faces all different from each other?

If a brass block is held clamped between two horizontal surfaces, are the forces exerted by them upon the block equal?

**47.** Examine next the conditions as regards pressure in a column of liquid, $A_1B_1$ (Fig. 14, § 45), with "knees" at $E$ and $F$, the part $EF$ being horizontal, and $B_1$ at the same level as $B$. The value of the pressure at each level in the region $E$ is felt without change along a horizontal line between $E$ and $F$, being altered only when we turn up or down. But the vertical distance traversed in going from $CD$ to $BB_1$ is the same, by any track that runs out horizontally from $E$ until the rigid wall of the vessel at $F$ is reached, and afterward turns down a vertical line of increasing pressure to $B_1$. Consequently the pressures at $B$ and $B_1$ are equal.

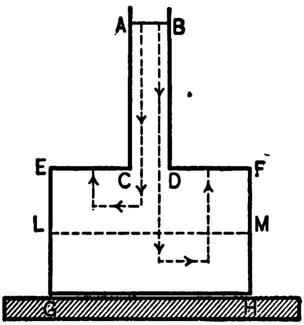

FIG. 16.

The open vessel $ABGH$ (Fig. 16), containing alcohol to the level $AB$, stands on a level base $GH$, and is made up of a cylinder $EFGH$ ($EF$ being horizontal) terminated by a vertical tube $ABCD$. The heights $HF$ and $DB$ are 10 cm., 40 cm., in that order; the area of the base $GH$ is 200 □ cm.; the cross-section of the tube is 15 □ cm. Assume atmospheric pressure to be 1000 gr.-wt. (to 1 □ cm.), and calculate the pressure at the level $LM$, half-way between $E$ and $G$. How much is the total force downward through the liquid at that level? What fraction of it is

due to atmospheric pressure at *AB*? The remainder is equal to the weight of how many cubic centimeters of alcohol? How many times greater is that remainder than the weight of the alcohol above the level *LM*? How many grams-weight is the upward force exerted by the alcohol against the cover *EF*, and what causes this force?

How do you account for the fact that the effort required to support the vessel and its contents is only equal to their weight, and is less than some of the forces calculated above?

In which of the previous answers does it appear that *force* applied to a liquid may be multiplied in amount by the process of transmission? Invent an arrangement in which force is reduced by transmission.

Trace the *pressure-values* along the two dotted tracks from *AB* to *EF*, and show that the pressure obtained for the level *EF* is the same.

## MEASUREMENT OF ATMOSPHERIC PRESSURE

**48.** Atmospheric pressure has been taken into account in the preceding sections, because it enters practically into the conditions under which liquids are commonly found on the earth's surface. But it is plain that we have in this action of the atmosphere only one special instance how a pressure may enter a liquid from the region around it and be handed on. Experimentally, atmospheric pressure can be replaced by equal pressure of other origin, over all or part of the free surface, without affecting the balanced conditions within the liquid. One instructive example of this is represented in Fig. 17.

Mercury is standing in the vessel *CD*, with atmospheric pressure exerted over the surface *A*, while there is an upright cylindrical tube containing mercury above the part *B*. The air has been removed from the space *V* over the mercury, which is protected from atmospheric pressure by closing the upper end of the tube (Ex. 25). Then the pressure at all points between *V* and *B* is due to weight of mercury in the tube alone. Throughout the level comprising the regions *A* and *B* there is uniform pressure; the mercury column resting on *B* is a complete equivalent for the air above *A* as regards production of pressure at the level of the free surface and below it.

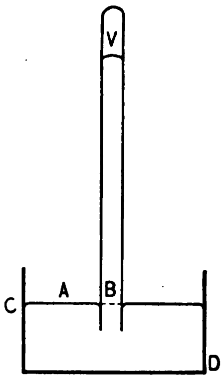

FIG. 17.

How does a contrivance of this type enable us to measure atmospheric pressure? By how much does the result of your measurement differ from 1000 gr.-wt.?

In what respects would this plan of measuring atmospheric pressure need modifying, if the mercury tube were (1) not of equal cross-section everywhere, and (2) not vertical?

What would you name as the source of the upward force at *B* (Fig. 17), which supports the weight of the mercury column *BV*? Is the source of the upward pressure at a given square centimeter of *A*, exerted by the mercury against the lowest layer of air, to be located at any *particular part* of *A*, or of *B*? Would the balance be disturbed by increase or decrease of pressure at *any* square centimeter of *A* or *B* (see § 45)?

The above method of securing a vacuum, and of finding a measure of atmospheric pressure, was invented by Torricelli (Ref. 6). The free space left in the upper part of such an inverted tube (or an equivalent arrangement) is still distinguished from a vacuum obtained in other ways; it is the "Torricellian vacuum."

If glycerine or sulphuric acid is used in a Torricellian tube, instead of mercury, how would you calculate the height corresponding to $BV$ (Fig. 17)?

What would you propose as a device for measuring air pressure in a diving bell?

## THE PRINCIPLES OF PASCAL

**49.** We shall need presently to dwell further upon contrivances for producing liquid pressures, and for holding them balanced. But before going on to do that, let us sum up the leading ideas of the sections just preceding this one. They were formulated long ago by Pascal, in two principles that continue to bear his name (Ref. 7): —

I. A liquid transmits pressure applied anywhere at its boundary throughout the space occupied by it, making an equal pressure (not in general an equal force) felt at all its parts and in all directions.

II. The effect of a liquid's own weight is felt as an additional pressure, also equal in all directions at any one place, but uniform on the same level only, and varying with the depth. This pressure is calculable for any level as the weight of one cubic centimeter of the liquid, multiplied by the number of centimeters in the depth of that level below the free surface.

## PRESSURE IN GASES

**50.** The mobility of liquids,—that is, their property of flowing freely,—has been brought into close connection with their exhibition of pressure in all directions without distinction. And this prepares the way to include all fluids in the scope of Pascal's principles. For the mobility of gases is one of their striking characteristics; and the force that any volumes of gas exert outward at their boundaries was referred to in first speaking of them.

When we pass from liquids to gases, the second principle becomes relatively less prominent, because the specific weight of gases is comparatively small. In order to gain a definite idea on this point, suppose that a pit 10 meters deep is filled with air of uniform specific weight 0.0012; take for the atmospheric pressure at the earth's surface a value that you have found by experiment, and calculate the pressure at the bottom of the pit. How many per cent is this greater than the pressure at the top?

Confining ourselves at first to the idea of transmission of unchanged pressure (Principle I), let us trace a typical step or two in the history of some portion of gas that occupies a completely closed space. It is instructive to see how certain conditions of pressure are established.

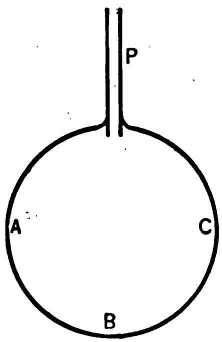

FIG. 18.

Take a toy balloon of rubber, for instance. In blowing it up with gas, a pressure greater than atmospheric pressure was exerted in the opening of a pipe *P* (Fig. 18). The process can be stopped at any

stage, and the balloon be just kept distended by maintaining the requisite pressure in *P*. This pressure is transmitted and felt equally at all parts of the rubber envelope, in conformity with Pascal's first principle. If now a string be tied tightly round the neck of the balloon, so that communication with the pipe is cut off, the rubber in the neighborhood of the string supplies permanently the pressure that was originally brought to bear through the pipe. Again, in pumping up a bicycle tire, the pump causes a pressure in the connecting pipe, and onward into the tire when the check-valve is opened. When the valve shuts, it only holds the pressure that has been transmitted already to the inside of the tire everywhere.

In either of these cases, the passive resistance demanded of the completely closed vessel, in order to meet the outward pressure of the air or other gas, is a sort of permanent record. It tells how far an active process of compression was once carried on, through an opening in the walls.

Can you detect similar conditions in the so-called "siphons of soda-water"?

What other instances do you discover in your experience, where outward pressure in all directions is a reaction against previous compression? Are they limited to fluids? Do they include liquids as well as gases?

### THE BAROMETER

**51.** But we can shut off a portion of gas at ordinary atmospheric pressure; for example, by putting a stopper in an open bottle of air. It is fair to ask, "Does the pressure of this air against the inside of bottle and stopper register the result of some previous process of compression?"

Soon after atmospheric pressure was measured by Tor-

ricelli, Pascal himself suggested that its cause is to be sought in the weight of a vertical column of air, reaching up to the limits of our atmosphere. This is at least a considerable number of kilometers high, and the accumulated weight that rests on one square centimeter, — that is, the pressure due to weight of air, — may thus become very perceptible, although it eludes observation on a smaller scale. One effect of that weight would certainly be to compress the lower layers of the atmosphere, and to compress them more strongly near the earth's surface than at an elevation of two or three thousand meters. On this supposition regarding the main source of atmospheric pressure, it was expected that the column of mercury $BV$ (Fig. 17, § 48) would become progressively shorter, when such a Torricellian tube was carried from the foot of a mountain to its top. This test was really made according to Pascal's directions on a mountain called Puy de Dôme, in central France (Ref. 8), and the result confirmed his expectation. He was aware beforehand that the mercury sank in the tube when air was in part pumped out of the region $A$, for he had tried that experiment. It remained to furnish directer evidence (as the trial on the mountain did) that the atmospheric pressure at $A$ has the weight of superincumbent air for its *chief* source.

**52.** The essential features of a Torricellian tube are incorporated in the instrument now universally known as a **barometer**[1]; the information is widespread in these

[1] We shall use this word to designate the *mercury* barometer (Fig. 17), and reserve descriptive adjectives for other (less common) forms, which will be alluded to later. Does the etymology of "barometer" contain any suggestion of weight?

It ought not to be left unmentioned that small contributions to the

days that the "barometer reading" is regularly less at the top of a mountain than at its foot; and the conclusion has come to seem almost instinctive that the indicated pressure is lessened by getting rid of the lower layers in the atmosphere and their weight. But we must realize the uncertainty about this matter that beset the best minds in the year 1646, and the constant need of resorting to experiment in order to settle such questions.

The daily or hourly record of atmospheric pressure that is so important in meteorology is made in terms of "barometer height," as so many centimeters (or inches) of mercury. Show the fuller meaning of the phrase by translating the reading 75 cm. into pressure (grams-weight on 1 □ cm.).

In making that first trial on Puy de Dôme, two barometers were actually read simultaneously, at times previously agreed upon; one instrument being stationary at the base of the mountain, while the other was carried up. What reason can you see for taking this precaution?

As the average of many such observations, it is known that the barometer "falls" about 0.9 cm. for each added 100 meters of elevation above the sea-level, up to 1000 meters. In the historical experiment, the ascent was nearly 900 meters. According to your knowledge about the daily fluctuations of the barometer height, would a single trial with one instrument have been fairly conclusive to Pascal?

The barometer readings in two places are 70 cm. and

barometer indication are introduced by violent winds, revolving (cyclonic) storms, etc. The barometer measures the local pressure of the air, however caused; but weight is emphasized as the chief source of atmospheric pressure.

75 cm. When we conclude that the corresponding atmospheric pressures are in the ratio $\frac{14}{15}$, what assumption do we make about the weight of 1 c.c. of mercury at those two places? The facts justify that supposition for ordinary purposes, as we shall see when we come to know them more completely.

Since the real atmospheric pressure is not steady at one place, nor the same at different places, a sort of standard value has been selected, and called an **atmosphere**. One atmosphere of pressure corresponds to a barometer reading of 76 cm. Convert this reading into pressure, if 1 c.c. of mercury weighs 13.60 gr.-wt.

**53.** Provided that we are dealing with vertical distances so short that we can afford to disregard *changes* in specific weight for air, due to *different* compression at various levels in the air column, the principle of Pascal as stated in § 49 will still apply. And the conclusions drawn for air in this respect can be transferred to other gases, because all the essential conditions are repeated in them.

Assume air to be homogeneously of specific weight 0.00122 (a close average value), and calculate the "fall of the barometer" for the first 150 meters of elevation above the sea-level. Compare the result with 1.5 times the average fall for each 100 meters given above, and judge whether there is present need to take account of variations in compression of air produced by its own weight, within a vertical range like the height of a building.

## ELEMENTS COMPOSING BUOYANT FORCE

**54.** In Chapter II definite values were established for buoyant force, as a total or aggregate effect. Let us

return to those results, and bring to bear upon them the view of fluid pressure that we have now secured; it will enable us to take one further step, and see how the total buoyancy is built up from the elements that enter into it. The diagram (Fig. 19) shows a closed vessel, *ACD*, containing homogeneous liquid to the level *AC*, the space *S* being occupied by gas at any pressure. A right-angled block *B* of any (insoluble) substance is submerged, its base being horizontal. Draw any horizontal line, 12, perpendicular to either pair of the vertical faces. Then the pressures against the block at 1 and 2 will be equal and opposite, *wherever the line is drawn;* the entire set of pressures against one face exactly match and offset the other set against corresponding parts of the second face. The block is squeezed equally from both sides, but not pushed as a whole in a horizontal direction. Draw now any vertical line, entering the block at 3, and leaving it at 4. Whatever pressure is exerted in *S*, the upward pressure on the block at 4 *exceeds* the downward pressure at 3 by the same amount — the weight of a column of the liquid having upper and lower bases of 1 □ cm. area in the horizontal faces of the block. Since the whole volume of *B* can be regarded as equivalent to a group of such columns, it is evident that the sum of these *differences* of pressure will yield a total upward force whose magnitude is expressed in the principle of Archimedes (see § 30).

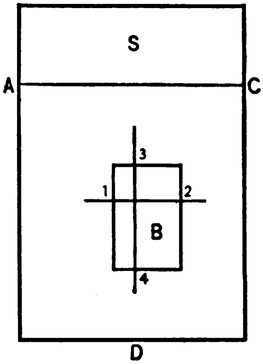

FIG. 19.

**55.** Bodies are not always right-angled blocks, however; so we shall consider one that has an irregular surface like *B* (Fig. 20). In that case we may imitate the body in shape and volume by fitting together fine rods of the same substance, and cutting them off *square* to the proper lengths; the reproduction of *B* being closer, as the rods are taken finer. Of course the rods may be laid in any direction and yet imitate *B*, if cut to the necessary lengths; the diagram shows bundles of rods forming *B* according to two plans. The first is indicated by the horizontal line 12 and the lines parallel to it; this scheme is convenient to think of in connection with horizontal pressures. The second is represented by the vertical line 34 and its parallels; these are useful in collecting the elements of vertical force exerted upon *B* by the liquid.

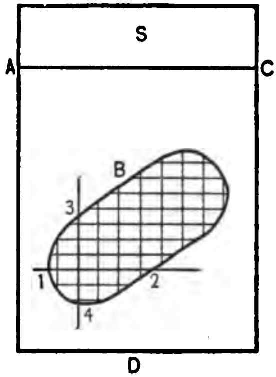

FIG. 20.

The reasoning of the preceding section can be applied to each individual rod of either bundle. Thus, the pressures on the ends of a rod parallel to 12 are equal at corresponding parts, and consequently no balance of force in either direction is left, no matter whether we build up the bundle of many rods or of few. Again, if we choose a vertical rod like 34 and its companions, there is an excess of upward force exerted by the liquid, equal to the weight of the latter which that rod replaces. Adding together these effects, the upward force is equal to the weight of the liquid replaced by the entire bundle of rods,

whatever their number. Remember, moreover, that we always come *nearer* to reproducing the actual solid in material, shape, and volume by *increasing* the number of rods. Hence we conclude that here, too, the principle of Archimedes expresses the final result.

The method of these two sections can be at once applied to a body surrounded by any gas that may be regarded as homogeneous.

In Fig. 16 (§ 47), the atmospheric pressure on $AB$ is not exactly equal to that on $EF$. Why? Does this difference make the final upward pressure against $EF$ a little less, or a little greater, than that due to the weight of the liquid column $ABCD$?

A tin can, $C$ (Fig. 21), is closed air-tight and floats in water. Why does atmospheric pressure on the upper face of $C$ not force the can down into the water? If the can does not "spring" under the pressure, will the immersed volume change *at all*, when the air pressure on water and can is increased or diminished?

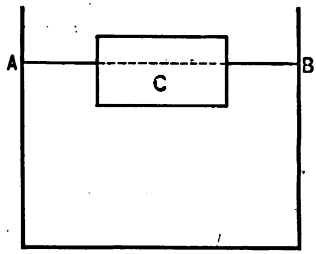

FIG. 21.

Suppose that the can is so ballasted with lead that it floats with its upper face in the free surface $AB$. Does the buoyant force balance the weight of metal alone, or of metal and of air contained in $C$?

## THE PRACTICAL IMPORTANCE OF PRESSURE

**56.** In this whole discussion touching the conditions within a portion of liquid or gas, it can be seen how

naturally our attention is drawn to the idea of "pressure," when we come to describing the facts. Note, too, that popular modes of thinking have anticipated the prominent part assigned to that idea, although the real intention is oftentimes obscured by shorter or looser forms of speech. We are told, for example, that the reading on an ordinary steam gauge is sixty, when the boiler "carries sixty pounds of steam." The truer thought underlying the quoted phrase is that each square inch of the boiler's walls is called upon to withstand a force equal to 60 lbs.-wt. (see § 22, end); that is, the pressure of the steam is 60 lbs.-wt. (on 1 □ in.) in excess of the atmospheric pressure. Reduced to our adopted units, this amounts to about 4200 gr.-wt. (on 1 □ cm.).

So we hear the standard atmospheric pressure (1 atmosphere) spoken of as "fifteen pounds to the inch." How would you improve this expression? Does the numerical value agree accurately with the statement in § 52 of what is meant by one atmosphere?

The term "head of water" is only water pressure disguised. Water is said to stand under a head of 100 ft. (= 3048 cm.), when it exceeds the atmospheric pressure by a force on each square centimeter equal to the weight of a water column standing on that base, and 3048 cm. high. The usage which states water pressure as head (*i.e.* feet of water) is entirely parallel with that which reads and records atmospheric pressure as "centimeters of mercury." Why do these more popular terms practically subtract the atmospheric pressure, and count only what is in excess of it?

Calculate the water pressure corresponding to a head of 150 ft. How many atmospheres is it?

In practice, the intensity with which force is accumulated upon unit area becomes the deciding factor, wherever the strength of materials is called upon to withstand the force. When stone blocks are fitted together, or a tie-rod is put in, or joists rest on walls, or belts carry power to pulleys, force in relation to area is more important than total force. If the bearing-surface or the cross-section be taken large enough, the weight or other force can be distributed uniformly, making the share of each unit area small. Thus snowshoes may render it possible to walk over thinly crusted snow. And, reversing the conditions, rivet holes can be punched in a steel plate by concentrating the whole available force upon the small area of the hole.

In connection with liquids and gases, the notion of total force (as distinguished from pressure) becomes not only secondary in this sense, but also indefinite, because the force can be multiplied at will by increasing the area to be considered (see § 47). We should be on our guard, however, against imagining that there is anything mysterious about this "generation of force." Recollect that force is multiplied in a large ratio, also, in using a simple crowbar.

## EXAMPLES OF FLUID PRESSURE

**57.** Air pressure is one of the necessary conditions under which we spend our lives, and enters, with water pressure, into many combinations that are of everyday utility. Consequently, instructive illustrations of the ideas developed in this chapter confront us on every hand. We shall encourage the further study of such actual contrivances by giving an outline of the way in which a few

of them act, besides suggesting some more obvious instances in the form of questions or problems.

The simple and powerful machine known as the **hydrostatic**[1] **press** (or hydraulic press) is a direct application of Pascal's first principle. Two cylinders, $C$ and $C_1$ (Fig. 22), are connected by a pipe $B$, and fitted water-tight with movable pistons, $P$, $P_1$. The circular cross-section of $C_1$ is much larger than that of $C$ — perhaps in the ratio $\frac{100}{1}$. Water from the tank enters at $V$, keeping $C$, $C_1$,

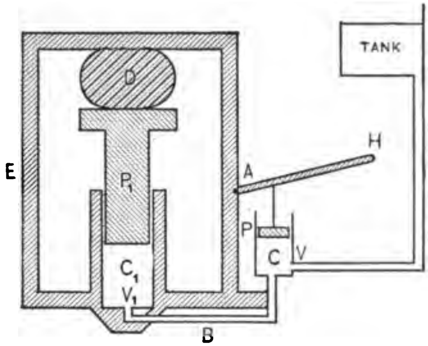

FIG. 22.

and $B$ always full. A strong rigid frame, $EA$, is attached to the cylinder $C_1$, and the piston $P$ can be moved up and down by the handle $H$. When $P$ is driven downward, communication with the tank is cut off by the valve $V$, and water is forced into $C_1$. A valve $V_1$ prevents this water from flowing back when $P$ is raised to repeat the stroke; but $V$ allows a fresh portion of water to fill up the cylinder $C$. Show on the diagram a possible arrangement of $V$ and $V_1$ to effect these objects. In this way, pressure is applied to the water at $P$, and transmitted to $P_1$, with the result that any object $D$ is squeezed between the upper face of $P_1$ and the top of the frame.

[1] Look up the meanings of the two parts which compose the word hydro-static.

Would atmospheric pressure alone, on the upper faces of $P$ and $P_1$, cause any motion, or are its effects balanced?

In what relative position of $P$ and $P_1$ would the weight of the water in $C$, $B$, and $C_1$ be without influence? On the practical scale, the effective weight of either water or pistons is likely to be only a small fraction of the forces called into play in the hydrostatic press.

Two men, with ordinary leverage on the handle $AH$, can easily bring to bear on $P$ a downward force of 750 kg.-wt. Supposing the circular cross-section of $C$ to be 20 □ cm., and that of $C_1$ to be 2000 □ cm., how great an upward force will be exerted against $P_1$? How far will $P_1$ move upward, for a down-stroke of 25 cm. at $P$? Show how the press could be used to determine whether a sample of building stone would sustain a *pressure* of 1 ton-wt. (to the square inch).

The hydrostatic press is likely to be employed where the force with which $P_1$ is urged forward must be great, while the motion of that piston is slow and repeated on a short range. It would be effective, for example, in baling cotton, or in making books flat and compact after binding them. It is frequently used in crowding car-wheels on to their (tight-fitting) axles, and forcing rings on steel shafts or guns, to strengthen them. Presses are constructed which give much greater force than that calculated in the numerical example above.

**58.** The tube $T$ (Fig. 23), standing in a vessel containing water, is open at the lower end, and the movable piston $P$ fits it air-tight. The water inside and outside the tube stands at the same level, so long as there is an opening at $A$ below the piston. If now $A$ be closed, why will the

water level within the tube change when $P$ is moved up or down?

Show that this idea, together with the play of two valves, accounts for the action of the lifting-pump in raising liquids (Ex. 26). In what respects does the force-

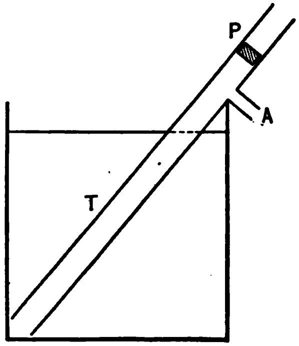


FIG. 23.

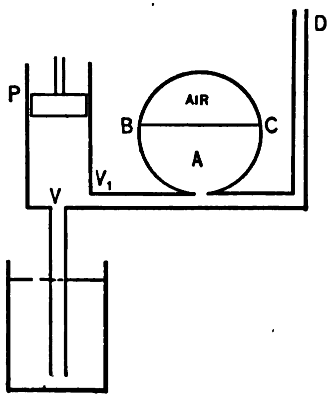


FIG. 24.

pump differ from the above lifting-pump? This skeleton diagram of the former (Fig. 24) shows an arrangement for delivering water at the top of a pipe $D$. The air-chamber $A$ contains air above the level $BC$, and water below it. In which direction should the valves $V_1$, $V$ open? When the pump is in use, the flow of water at $D$ becomes less jerky or intermittent, because of the air pressure in $A$. Explain how the air-chamber operates to produce that result.

What considerations set the limit on the height to which a *perfect* lifting-pump could raise water? Contenting ourselves with 75 per cent of the maximum, to cover defects in the pump and secure quicker flow, calculate this

*practical* limit in pumping brine or sugar-syrup of specific weight 1.10.

The so-called medicine dropper consists of an open glass tube *T* (Fig. 25), ending in a hollow rubber ball *B*. In filling the tube for use, the ball is first squeezed flat; and it is not released, until the end of the tube has been dipped below the surface of a liquid. What happens then, and why? In "sucking up" water through a straw, the cheeks with their muscles replace the bulb *B*. Does unequal air pressure *drive* the liquid in these cases, or is it *drawn* up by a "force of suction"?

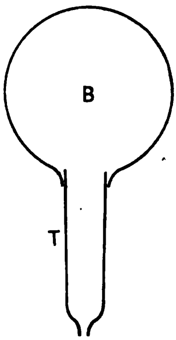


FIG. 25.

**59.** *AB* (Fig. 26) represents the free surface of mercury in an open vessel. The tubes 1, 2, 3 are all closed at their upper ends, and they open below the surface *AB*. All three contain mercury, 1 and 2 being completely filled with it, while air occupies the space *V* in 3. What measurements would you make, in order to determine the air pressure in *V*? Show that the pressures in 1 and 2 must be equal to those in 3 at the same level. In 3, air presses down upon the mercury at *C*; what presses down upon the mercury at the top of tube 2? What elements

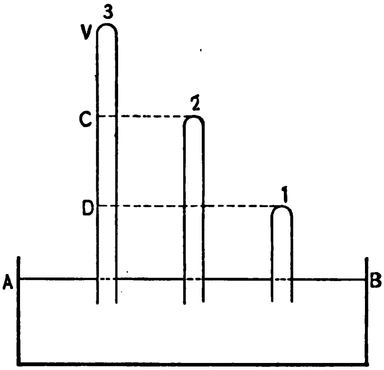


FIG. 26.

make up the pressure in the mercury at the layer *D*? How is equal pressure exercised on the mercury at the top of 1? If the air above *AB* is pumped out, at what air pressure will the mercury leave the top of 2? of 1?

The "vacuum gauge" of an air-pump is often a shortened barometer like tube 2 or tube 1, not indicating pressures greater than 0.1 of an atmosphere.

**60.** In pumps we see atmospheric pressure utilized as a means of raising liquids to higher levels. Another contrivance operated by atmospheric pressure is the **siphon**, represented by the bent tube (Fig. 27). When once filled with liquid and started, a siphon will carry liquid automatically over a considerable elevation; but the liquid moves down hill through the siphon finally, to the extent that it always flows toward the place where the free surface is lower (provided the vessels are open); and the flow ceases when the free surfaces in two vessels like *A* and *C* are at the same level (Ex. 27).

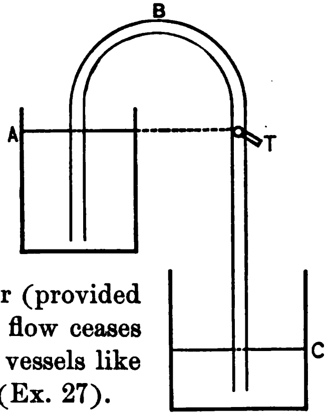

FIG. 27.

In order to understand its action, think of the siphon as filled, while it dips into liquid at *A* and *C*, and flow is prevented by a closed tap *T* placed in the same level with *A*. Then just the full atmospheric pressure is transmitted to the upper face of the tap, because *A* and *T* are at the same level. And, as regards the lower face, the weight of the liquid between *T* and *C* causes the pressure there to be less than the atmospheric pressure at *C* (see § 59). But, if *T* be placed

higher or lower, the same inequality persists, for equal amounts of pressure are added or subtracted at both faces (remember Euclid, Axiom 2). Hence, at every layer of liquid in the tube there is unbalanced pressure toward $C$, and consequently the flow of liquid is in that direction on opening $T$.

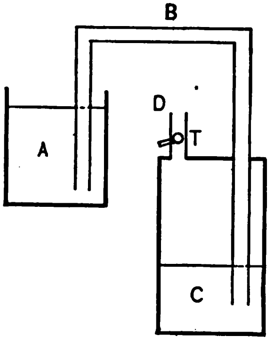

Fig. 28.

If the elevation of $B$ exceeds a certain value, with a given liquid, the column in the siphon breaks, part running back into $A$, part into $C$ (Ex. 28). What do you recognize as fixing the critical height at which the column of liquid breaks? Does this behavior depend upon the difference of level $BA$, or upon $BC$?

Suppose the levels to be such that the siphon will act, the lower vessel being covered air-tight, and access of air to it being governed by a tap $T$ (Fig. 28). Why can the siphon be filled by "suction" at $D$? After starting the siphon, let $T$ be closed. How do you express the conditions when the liquid ceases to flow, before the supply in $A$ is exhausted?

**61.** Common usage attaches the word "siphon" in a misleading way to one or two cases where a liquid occupies a tube or pipe in the general form of an *upright* U. Where a water-main crosses a valley by following the ground surface, it is often said to be an "inverted siphon"; and the so-called "siphon barometer" is arranged as shown in the diagram (Fig. 29), the tube

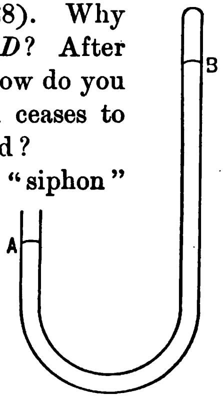

Fig. 29.

being completely filled with mercury between the levels *A* and *B*. There is nothing characteristic of the siphon in these contrivances; they can be connected directly with Fig. 10 (§ 38), and the general idea that liquids transmit pressure along curved channels.

A tube of any form containing liquid can be thought of as separated from a larger supply by putting in the necessary partitions. The dotted lines (Fig. 30) indicate the walls of a U-tube within which a portion of liquid may be isolated from the rest, without changing the distribution of pressures. Practically, the same result follows when the liquid displaces the air from a tube of this form, on sinking its open ends (or one end) below the free surface. We say that the same pressures are exercised at the boundary of the liquid within any such dotted outline, (1) when it is just part of the larger vessel's contents, and (2) when it is enclosed in a tube of some solid material. How are the pressures brought to bear differently in the two cases, upon the liquid inside the boundary?

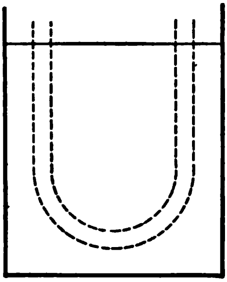

Fig. 30.

In this fashion, the siphon barometer can be "carved out" of the diagram (Fig. 17, § 48); put in the dotted lines to show this. What vertical distance is the barometer height in Fig. 29? Need the tube be of equal bore on both sides of the bend?

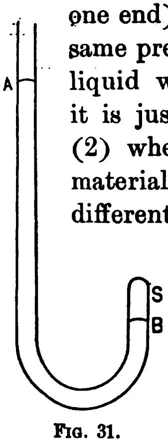


Fig. 31.

The tube *AB* (Fig. 31) is open at *A*, and contains mercury between the levels *A* and *B*, gas in the space *S*

above $B$. How would you measure the pressure exerted by the gas, or upon it; that is, the pressure of mercury and gas upon each other at $B$?

How can equivalent bent tubes be substituted for 1, 2, 3 and the vessel (Fig. 26, § 59)?

What connection exists between the conditions under which Artesian wells are found (Ref. 9), and those of an inverted siphon in a water-main?

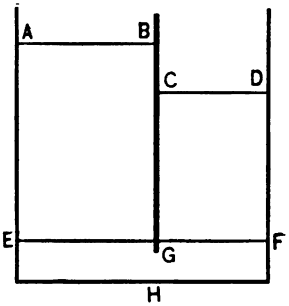


FIG. 32.

**62.** The open vessel $AHD$ (Fig. 32) is divided by a liquid-tight partition $BG$, in which there is an opening $GH$. Mercury stands at the level $EF$ (above $G$), and then kerosene is poured in on one side of $BG$, water on the other side. The free surfaces of kerosene ($AB$) and water ($CD$) are so regulated that the mercury surface is still at the same level on both sides of the partition. Will the positions of $AB$ and $CD$ depend upon the atmospheric pressure? In what relation do the (vertical) heights $EA$ and $FD$ stand to the specific weight of kerosene? Can water be substituted for mercury below the level $EF$, without affecting the levels $AB$ and $CD$?

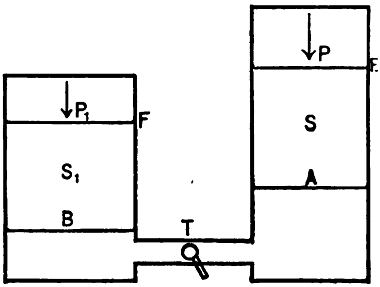


FIG. 33.

Explain the connec-

tion between the foregoing case and the methods of determining specific weights for liquids (Ex. 29; Ex. 30; Ex. 31).

Two closed vessels, $A$ and $B$ (Fig. 33), are connected by a tube in which is a (closed) tap $T$. Mercury fills the tube, one vessel to the level $A$, and the other to the level $B$. Above the mercury is liquid of specific weight $s$ to $E$, and of specific weight $s_1$ to $F$. The upper parts of the vessels are filled with air at pressure $P$ (in $A$) and $P_1$ (in $B$). What condition must be fulfilled, if mercury does not flow through the tube when the tap is opened?

## CHANGE OF VOLUME IN GASES

**63.** We have repeatedly dwelt upon the fact that the tendency of a state of pressure within a fluid is to produce compression by squeezing its parts together (for example, see § 46, § 51). In liquids the reduction of volume consequent upon pressures of ordinary magnitude cannot be made visible and measured, except by refined experimental methods (Ref. 10); liquids are indeed often called *incompressible* fluids. But with gases the case is different. If we isolate any definite portion of gas, so that its behavior in this respect can be observed, we find moderate changes of pressure connected with marked changes in volume.

Taking the apparatus in the form presented to you (Ex. 32), how can it be seen at once whether the pressure of the enclosed gas ($P$) is greater or less than atmospheric pressure ($P_A$)? In finding $P$, does $P_A$ need to be known? Is the plan of *taking* measurements different, when $P > P_A$, and when $P_A > P$? Do you *combine* the measurements

differently in the two cases, to obtain the pressure of the enclosed gas?

Experiments of this nature have been made, covering a large range of values for pressure and volume; and they include many kinds of gas. For example, oxygen, hydrogen, nitrogen, that are classed as chemical elements; chemical compounds like marsh gas, carbon monoxide; and mixtures of either elements or compounds in given proportions, like coal-gas or air. So long as minute accuracy is not required, the results are expressed satisfactorily in a simple relation between pressure and volume. Though changes occur both in the volume and in the pressure of a given weight of any gas, the product of any value of the pressure by the corresponding volume remains unchanged.

If the volume of the same enclosed gas is $V$ c.c. when the pressure is $P$ gr.-wt. (on 1 □ cm.), $V_1$ c.c. for the pressure $P_1$ gr.-wt., $V_2$ c.c. for $P_2$ gr.-wt., etc., the relation can be indicated by the equality,

$$PV = P_1V_1 = P_2V_2, \text{ etc.} \tag{5}$$

Hence the ratios are equal,

$$\frac{P}{P_1} = \frac{V_1}{V}; \ \frac{P}{P_2} = \frac{V_2}{V}; \ \frac{P_1}{P_2} = \frac{V_2}{V_1}; \text{ etc.} \tag{6}$$

Express in your own words the rule contained in the equalities (6).

The first discovery of this rule is conceded to Boyle (Ref. 11); and it is frequently quoted as Boyle's Law. The experimental conditions under which it holds good are limited in two respects: —

(1) The gas must be guarded against becoming hotter or colder while the experiment is in progress.

(2) The pressures exerted must not condense the gas into a liquid.

As regards (1), heating a confined portion of gas with a flame shows increase of volume if the pressure is not changed, or added pressure if the gas is prevented from expanding (Ex. 33). The limitation (2) is less sharp. Condensation is produced in some gases by increase of pressure (Ex. 34), without cooling them; and those instances are at once rejected in which the gas actually condenses. But noticeable deviations from the rule may appear, even before condensation begins to be visible; to fix the point at which the rule shall be abandoned is then a mere question of accuracy (Ref. 12). A gas that is close to the conditions under which it condenses is often distinguished as a **vapor**. If we speak of any gases as vapors, we shall imply that they do not follow the rule expressed in Equations (5) or (6).

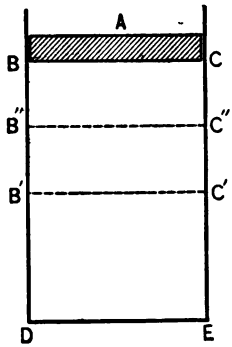

FIG. 34.

**64.** The cylinder $BCDE$ (Fig. 34) is filled with any gas at the pressure $P$. Let now the piston $A$ be moved down, and held with its face $BC$ at $B'C'$ ($BB' = \frac{1}{2}BD$); then the gas formerly in the upper half of the cylinder, and exerting the pressure $P$ there, is squeezed among the parts originally exercising an equal pressure $P$ in the lower half. With the piston at $B'C'$ the pressure below it is $2P$, if Boyle's Law holds true, just as though the added gas carried its pressure $P$ with

it to the space into which it is forced, increasing by just so much the other pressure $P$ previously existing there. The same pressure is exerted by the gas in either equal volume (upper half or lower half), whether that volume be shared with other portions of gas or not. Each portion produces its part of the total pressure independently. In the next place, suppose $BB'' = \frac{1}{4}\ BD$, the pressure in the shortened cylinder becoming $\frac{4}{3}\,P$, when the piston is moved down to $B''C''$. If the gas occupying the upper *one*-quarter at the pressure $P$ were transferred to the lower *three*-quarters, no other portion of gas being present there, the pressure would fall off to $\frac{1}{3}\,P$, because the volume is multiplied by three. But the result shows that the gas coming into the lower part from the upper quarter carries the same pressure $\frac{1}{3}\,P$ into the lower three-quarters of the cylinder, when gas exerting the pressure $P$ is there already. For $\frac{4}{3}\,P$ (the actual pressure) $= P$ (constantly exerted by the gas originally in $B''C''ED$) $+ \frac{1}{3}\,P$ (due to gas received from the upper quarter and expanded into the lower three-quarters). This conclusion can be extended easily to the other positions of the piston, above or below $BC$. Hence the rule of Boyle gains a new meaning, when viewed in this light; we may say that each portion of gas put into a given volume, or taken out, carries with it the pressure which it would exert, if it had that volume all to itself.

The chief constituents of air are oxygen and nitrogen, found mixed in very nearly the same proportion all over the earth — one volume of oxygen to four of nitrogen. Air in a closed vessel being at standard atmospheric pressure (see § 52), what fraction of this is due to oxygen, and what to nitrogen?

**65.** Since the volume of a given weight of any gas varies according to the condition of pressure within it, a measurement of volume for a gas is not a definite result unless the corresponding pressure is recorded also. It is found convenient to reduce measured gas-volumes to their values at the standard atmosphere of pressure. Show how that can be done, by calculating this "reduced volume" for 1200 c.c. of coal-gas, measured when the barometer reading was 74.5 cm.

How does the specific weight of any gas depend upon its state of pressure?

The diagram (Fig. 35) represents the essential part of an instrument for measuring depths in the ocean. The curved tube $ABC$ is closed at $A$ and open at $C$; it contains air, and is coated inside with a film that is visibly changed by contact with sea water. As the air within the tube is compressed under the water pressure, the salt water is driven in, and records its closest approach toward $A$. Boyle's Law furnishes a means of interpreting this mark in terms of depth.

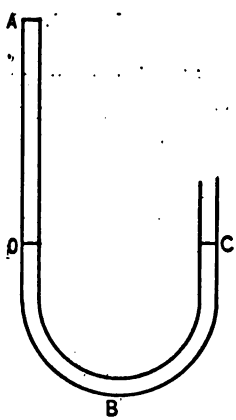

FIG. 35.

With water at the zero line for one atmosphere of pressure in $BA$, lay off along the tube a scale showing atmospheres of pressure on the contained air. Establish a numerical relation between this scale and fathoms of depth.

Show how buoyancy, transmission of pressure, and compression of gases are connected with Experiment 35.

Illustrate the difference between the weight of a gas, and the pressure that the gas exerts, by constructing an example in which the pressure is 100,000 times the weight.

# CHAPTER IV

## DIFFUSION, SOLUTION, CAPILLARITY

**66.** Experimental evidence from many sides points to the conclusion that substances in all three physical states have gaps or interstices among their parts. This idea was touched upon in Chapter I (see §§ 13, 15, 16); and we have returned to it in Chapter III, where we examined the conditions of pressure required, in order to force one portion of gas into a space already occupied by another portion. But when two substances are brought together, there are many instances where each one fits itself into the interspaces of the other without special effort on our part. Among the interesting phenomena that accompany such processes of spontaneous mixture, or result from them, the three types named in the heading of this chapter are now to be considered, of which two at least are familiar in several forms. Instances of capillary[1] action are presented when blotting-paper "soaks up" ink, or oil is drawn up in a lamp-wick; the solution of sugar or salt in water is an everyday occurrence; and as for diffusion, it plays an important part in the economy of our lives. If it escapes notice, that is not on account of its rarity, as we shall see, but because of other reasons.

[1] Notice the suggestion in the etymology of this word and its derivatives.

We confine ourselves to mixtures, and exclude what are usually called combinations, like that occurring between the parts of fuel and the oxygen of the air, when the former burns, though such processes may be vigorously spontaneous; and they do result, probably, in mixtures that are more intimate and thoroughgoing than any others. The systematic consideration of "combinations" is assigned to Chemistry; but the distinction between (physical) mixture and (chemical) combination is not always sharp and decisive. If one sign of chemical activity is self-heating during combination (as in combustion), some phenomena ordinarily treated as instances of solution (Ex. 36; see also Ex. 5) are on the *threshold* of combination, at least. We need not raise the issue of assigning doubtful cases to Physics or Chemistry, however; the more profitable question is about the nature of the phenomena as they present themselves (see § 5, § 12).

## DIFFUSION OF GASES

**67.** The first process of spontaneous mixture for us to take up is one in which both substances are in the gaseous state. If two jars, — one containing air and the other coal-gas (at equal pressures), — are placed mouth to mouth, their contents soon become a homogeneous mixture of the two gases (Ex. 37). In spite of the facts that the two jars are occupied beforehand at the same pressure, and that the specific weight of coal-gas is about half that of air, each gas proceeds to mingle with the other, and take its share in a joint occupancy of both jars. At any time during the process, or afterward, Boyle's Law applies to the mixture; so long as the internal volume of the two jars

is not changed, the pressure does not vary, provided always that heating and cooling of the gas are avoided.

With any such gases, in whatever proportions by weight or volume they are present, an internal readjustment goes on automatically in the direction of blending any number of unlike constituents into a homogeneous mixture; those which are specifically heavier do not "settle" into the lower part of the vessel. The name given in general to this process is **diffusion**. It is plainly evident in its consequences, but its details have not been detected by any experimental aid available at this date. The scale upon which diffusion is executed is invisibly small; it must not be confused in our thought with currents of air or other gas which are seen or felt. The consequences of diffusion are found in perfection, where circulation of gas "currents" is prevented as completely as possible.

Yet currents on the larger scale work with diffusion on the whole, and do not counteract nor oppose it. For they bring different portions of gas into contact, and stir them together, as it were, giving diffusion a better chance to remove any local excess of one constituent, by absorbing it into an average condition everywhere. The most striking exhibition of such tendencies toward homogeneousness is seen in our atmosphere. Animals are pouring into it their exhaled breath; plants are making local changes in it; and the same is true of chimneys with their smoke and other products. But the winds, aided by diffusion, keep the inequalities from accumulating, and maintain the atmosphere at a remarkably even composition the world over, and from year to year. The largest variation is in the proportion of water-vapor that is mixed with the other gases of the atmosphere.

**68.** The fact that gases diffuse into each other, and complete the process practically in a short time, under ordinary conditions, is strong evidence that their particles are moving around. Since the results are brought about without observable currents, the particles must move in smaller groups or individually, each group or single particle threading its way in such free spaces as open up among the others. Experiment 37 has some further lessons for us, drawn from the constancy of pressure when diffusion is going on. First, since the pressure ($P$) within the space does not vary while air and coal-gas are being interchanged between the jars, this substitution of one gas for another within the same volume is without effect upon the pressure. After the mixing is accomplished, the contents of each jar are (by volume) half air and half coal-gas. The air that is still present in the lower jar exerts a pressure $\frac{1}{2} P$ (see § 64), the remaining $\frac{1}{2} P$ being due to the coal-gas introduced in place of air. In the upper jar, a similar equal division of the pressure $P$ can be made, but there it is air that is introduced by diffusion, and coal-gas that remains. Secondly, if the coal-gas passed into the second jar by expansion, that space being originally a vacuum, the original pressure ($P$) would fall to the value $\frac{1}{2} P$ in that case also. The same would be true, likewise, for air expanding to twice its volume. So each of the two gases in this instance behaves with complete independence of the other, as regards its share of the pressure. That varies, for either gas, according to the entire volume which it permeates, and is unaffected by the presence or absence of the other gas as joint occupant.

The mixing of equal volumes has been discussed for air

and coal-gas, merely in order to speak of some definite case; but the same considerations apply to the mixture of other gases by diffusion, in any ratio of volume. Consequently, these conclusions enable us to extend the idea of § 64 to different gases, as well as to separate parts of the same kind of gas. Note in all these examples how the *original* volume and pressure for each constituent portion are given, as a means of determining the "pressure which it would exert, if it had [the new] volume all to itself."

It is said that the *final* result of diffusion *as regards pressure* is the same as though each gas expanded into a vacuum, instead of a space occupied by other gas. Is the result produced as rapidly by diffusion as by expansion? Measurement shows differences in the rates at which gases diffuse (Ex. 38).

**69.** After dwelling on these circumstances of gas diffusion, and following "with the mind's eye" the particles as they wander about and mingle, it is fair to ask, "Do such movements *begin* only when portions of *different* gases are brought into each other's presence?" In that event, there would be no interchange of particles between the jars in Experiment 37, if both contained air at the same pressure. Supposing, on the other hand, that the particles of any gas are always moving around with considerable freedom, two portions of one gas at equal pressures would diffuse into each other and mix; and the individual particles in any selected part of an enclosed volume would be changing continually. The particles are too minute to be traced on their excursions, so the directest evidence of their motion or rest cannot be furnished. Nor will effects of their motion accumulate and become observable, so long

as a new particle replaces one just like it, and leaves the properties of a gas unmodified. So we must be guided by indirect evidence (inference) in forming a mental picture of the conditions belonging to the gaseous state.

In which direction does the fact point, that a gas will spread indefinitely, when the volume in which it is enclosed is made larger?

Do the conclusions of § 64 and § 68 suggest essential and marked difference of internal condition between a homogeneous gas and a mixture?

Keep this matter in mind, without trying to give a final answer to the main question yet; watch for phenomena that offer additional light.

## SOLUTION OF SOLIDS

**70.** When a solid and a liquid are brought into contact, sometimes the former seems unaffected; it maintains its edges sharp, and its volume unaltered. It is then called **insoluble** in that particular liquid; thus iron and a number of other metals are insoluble in water; so are many varieties of rock. Or the lump of solid may become rounded at its edges, show decrease of volume, and disappear entirely, leaving a liquid that is opaque or transparent, colorless or colored, according to circumstances. Think of some examples. These are cases where the solid is **soluble** in the liquid, and yields a **solution**. A liquid that dissolves a solid is a **solvent** for the latter. Solutions are weak or dilute when they contain small proportions of dissolved solid; they become stronger or more concentrated as that proportion increases. The property of solubility (or insolubility) does not belong to any solid by itself, but to the

solid in its relation to some liquid; the solid may be insoluble in one liquid, soluble in another. Shellac dissolves in alcohol, but not in water; ether is a solvent for some fats, while alcohol is not; mercury dissolves many metals, forming solutions called amalgams, though those metals are insoluble in water, alcohol, ether, kerosene, etc. (Ex.).

The solvent action of a liquid upon a solid ceases at a certain concentration; the solution is then said to be **saturated.** It lies almost in the nature of this relation, that the saturation-point must be specially determined for each pair (Ex. 39). Concentration and saturation-point are often expressed numerically as so many grams-weight of solid to one cubic centimeter (or one liter) of solution. Whether the saturation-point is actually reached or not in a particular case depends, of course, upon the relative amounts of solid and liquid present; the supply of solid may be exhausted, before the solution becomes saturated. It is worth remarking that true insolubility is rarer than common speech would indicate. The term "insoluble" is often used where the saturation-point is low; that is, when a solid is soluble very sparingly, or "with great difficulty" in a liquid. Do you know of any evidence that rain water will not only "wear away" rock, but actually dissolve it?

The words "dissolve" and "solution" are frequently employed in a broader sense than that intended here, to include certain chemical actions and combinations (see § 66). Zinc is said to dissolve in sulphuric acid, and copper in nitric acid; but these are both complicated processes resulting in the formation of "new substances" (gases and salts). The (physical) solution seems to be a looser association, from which both solid and solvent can be regained by some such method as evaporation (Ex. 40).

## DIFFUSION OF LIQUIDS

**71.** When it is desired to make a solution (especially a strong solution), the solid and its solvent are commonly shaken together or stirred, because that brings fresh surfaces into contact, and secures the result more quickly. But at the same time some instructive phases in the process of solution are obscured, which can be observed when we guard against all agitation like stirring or shaking that produces visible currents of liquid (Ex. 41). Here the formation of concentrated solution immediately round the solid is succeeded by a spreading of that condition upward. Such action is spontaneous, it goes on *in spite of* the difference in specific weight between solvent and solution, and its details are invisibly minute. Although the completed result may be deferred for months, there is continual approach toward uniform concentration throughout the vessel. Under conditions of which this experiment is typical, different substances blend themselves into homogeneous mixture, just as coal-gas and air do in a previous instance, and at the expense of lifting a certain weight of solid through a specifically lighter liquid. This process of equalization between stronger solution and weaker is also called **diffusion** — liquid diffusion, where we need to distinguish it from gaseous diffusion. The final outcome is that the solid particles diffuse among those of the solvent, and through layer after layer of the latter to considerable distances. But several weeks may be required to transport a gram-weight of solid to a place only a few centimeters away. Dissolving the solid, and thus converting it into a liquid, is a preparation for the journey. The rate of travel varies according to the solid and the solvent used.

The transmission of pressure by liquids has been found to depend upon freedom of their particles to move (see § 45). What suggestion have we now that their particles are *actually wandering about* from place to place? How does the rapidity of the suggested motion compare in liquids and gases?

Gaseous diffusion can effect a homogeneous mixture, when gases are present in any proportion whatever. Liquid diffusion produces uniform distribution of one substance through another, but the possible range of its effects is limited. What consideration imposes the limits?

## SOLUTION OF LIQUIDS

**72.** When adjacent layers of a solution are at different concentrations, they are in many respects effectively different liquids. We have learned from what precedes that such liquids show a tendency to obliterate their differences, and produce automatically a homogeneous mixture. But these circumstances cannot be accepted as characteristic for every case, and a somewhat wider study of the facts soon enables us to recognize three types of result when different liquids are in contact (Ex. 42): —

(1) The liquids do not diffuse into each other; and if mixed by shaking or stirring, they separate again on standing, with a sharp boundary between them.

(2) They form a homogeneous mixture by shaking, by stirring, or (more slowly) by diffusion, in whatever proportions they are present.

(3) They yield mixtures only within a certain range of proportions. Outside of that range two layers form, and are separated by a sharp boundary.

The third of these groups provokes the thought that the action there is akin to solution; and especially the limit to the proportions of the mixture marks a stage like that of a saturated solution. Indeed, in all cases where liquids mix by diffusion, one does shade into the other, and efface the division between them, as a crystal loses its identity in its solvent. Note, further, that we rely upon diffusion to complete any intimate mixture called "homogeneous," even where we hasten the first approach to this condition by shaking or stirring.

Looking at all three groups from this point of view, we find the essential features of solution (as we already know them) repeated, both in the process and in the results, though we have substituted a second liquid for the solid of the previous instances. Accordingly, we describe the facts fairly when we say that ether forms a saturated solution with water; that water and alcohol are mutually soluble in all proportions; and that kerosene and water are insoluble to each other.

When alcohol and water are mixed, which is the *solvent?* If ether and water are poured into the same vessel, and the liquid separates into two layers on standing, is either layer pure ether or pure water? [A measurement of the specific weights will give a sufficient answer; but the ether used must be first purified; commercial ether is likely to contain both alcohol and water.] Which, then, is practically the solvent in this case?

## SOLUTION OF GASES

**73.** We have taken in succession two gases, a liquid and a solid, and two liquids, to illustrate how different

substances may accommodate themselves to joint occupancy of the same volume by forming one homogeneous mixture. A similar active tendency is shown between gases and many liquids. Gaseous ammonia is absorbed by cold water so vigorously that the gas taken up, unless thus imprisoned, would occupy about 700 times the bulk of the water, under the pressure of one atmosphere (Ex. 43). The bulk of carbon dioxide (carbonic acid gas) held under the same conditions is nearly equal to that of the water. Gases like hydrogen, oxygen, nitrogen, are absorbed by water and other liquids to a smaller extent, but still noticeably. These seem to be instances of solution, in all important respects resembling those considered previously. The gas-bubbles disappear in the process, and a clear homogeneous liquid is obtained, whose properties may differ from those of either the liquid or the gas separately. There are stages of concentration, and a saturation-point, too; the latter being sensitive to changes of pressure, as might be expected where a gas is concerned (Ex. 44). Diffusion is found to occur in these solutions; any excess of dissolved gas will move from layer to layer, its direction being from concentrated to dilute portions of the solution. Therefore the automatic process has the same general effect of removing differences of concentration, even where the relation of specific weights is such as to oppose equalization.

Solubilities do not fall under any simple rule in dealing with different liquids and gases; they range from practical insolubility (*e.g.* nitrogen in mercury) to "ammonia water" as an instance at the other extreme. We accept a fact like "Oxygen is more soluble in alcohol than in water" as recording an unexplained property of that gas

in its relation to the two liquids. Air consists chiefly of nitrogen mixed with oxygen; and it happens that the former gas is less soluble in water. Under these circumstances, the "dissolved air" of water is made up (by volume) of oxygen about one-third, and nitrogen two-thirds. The fishes profit in their breathing by this richer content of oxygen than is found in our atmosphere.

**74.** A change of volume often takes place when a solution is formed, so that it represents less than the added volumes of solvent and dissolved substance separately. The data of the preceding section make it apparent that a gas may be strongly condensed in entering the interspaces of the solvent liquid. The diminution of volume on mixing certain liquids was brought out in Experiment 5. The existence of similar conditions in dissolving solids can also be established readily (Ex. 45).

It is found that a solid dissolves more rapidly (without direct stirring) if hung in the upper layers of a solvent, than if placed at the bottom of the vessel; explain this fact.

What reason can you assign for the result, when a water-solution of iodine is shaken with chloroform or carbon bisulphide (Ex. 46)? Iodine is more soluble in these liquids than in water.

## DIFFUSION AND SOLUTION: SOME GENERAL CONCLUSIONS

**75.** It is clear that diffusion as we have been observing it in solids and liquids always proceeds in such fashion that the particles of dissolved substance spread through larger volumes, and consequently become more widely

separated from each other. When alcohol dissolves in water, some particles of each liquid must exchange neighbors of their own kind for particles of the other kind. Just so, dissolving salt in water substitutes particles of salt and of water as neighbors, where all was water before. Since the solutions and diffusions of which we speak go on automatically (when they occur at all), the substances appear to secure a gain or advantage of some sort by that form of exchange which we find actually happening. One way of putting the matter is to say that there is a gain in "stability"; for a condition of affairs is termed stable in proportion as things settle into it of themselves, and withstand attempts at change. It is often a troublesome problem to undo the effects of solution and diffusion. Secondly, we are still on safe ground in assuming that forces are in play during these changes of partners among the particles. As a net result of diffusion we can have weight overcome, and material lifted; so that the test is met which we have agreed to apply in recognizing forces (see § 25). A firm lump of solid, moreover, is reduced to a state of finest division in dissolving; and the muscular effort required to accomplish this in other ways is certainly appreciable. Let us prepare to carry our thought one step farther by examining first a few simple facts.

**76.** We have noticed that particles of the same sort (*i.e.* of the same material) hold together in solids, giving them strength (see § 34). In the uses of glue, mortar, rubber-cement, etc., we trust to the strength of a joint between unlike materials. There may be no necessity in general to distinguish between these two forms of strength; but it will save some words in the present

discussion if we discriminate by using **cohesion** for the first, and **adhesion** for the second. Suppose the wooden blocks *A* and *B* (Fig. 36) to be glued together at *G*, and pulled in opposite directions as shown by the arrows. Then we shall speak of strength as due to cohesion at sections made within one material, and due to adhesion at joints like *G* between two materials. The ideas are familiar in the present connection; but they can be traced elsewhere, with a little aid from experiment in following up the clews.

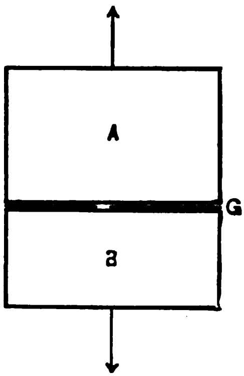

FIG. 36.

Adhesion between a liquid and a solid may be developed sufficiently to be measured (Ex. 47). Observe in which instances the liquid used "wets" the solid in contact with it.

Can you assure yourself that the effects seen here are not due to atmospheric pressure?

Cohesion among the particles of a liquid is not entirely lacking, although they have almost complete freedom to move in certain ways. If we look at all closely into the circumstances of Experiment 47, the consequences of liquid cohesion can be seen. In the first combination tried, the cohesion of mercury exceeded the adhesion between mercury and glass; the joint glass-mercury breaks, rather than the joint mercury-mercury.

How is the strength of the weaker joint measured in the experiment? What conclusions do you draw from each of the two other tests, about the relative strength of the cohesion and the adhesion shown? What new

significance do you discover in the fact that a liquid wets a solid? When a solid is wet by its solvents, what meaning can you attach to the fact? Do you know of any instance in which a solid is not wet by a liquid that dissolves it?

**77.** These less obvious forms of cohesion and adhesion have some bearing upon the phenomena of solution and diffusion. In dissolving a solid, its cohesions are somehow overcome; and this effect is certainly due to the presence of the solvent. Further, as was pointed out in § 75, the association of unlike particles is favored in the process of solution, as compared with the association of like particles. The indication is, then, that the greater stability established as a consequence of solution and diffusion, when they occur, consists partly, at least, in replacing weaker cohesion-joints (solid-solid; liquid-liquid) by stronger adhesion-joints (solid-liquid).

So much can be true without implying that *every* such adhesion-joint is stronger than *any* cohesion-joint; the excess of strength may lie now on one side, and now on the other, in particular instances. The conditions under which groups are formed spontaneously and at random in liquids cannot be expected to yield the same uniformity that is shown by the glued joints of the cabinet-maker, or the mortar-joints of the mason. But if the adhesion-contacts increase at the expense of the cohesion-contacts, that means, on the whole, that fewer of the latter are formed and more are broken, the balance inclining the other way for the adhesion-joints. Consequently, judging by the aggregate outcome in a very large number of instances, the adhesion-joints are on the average stronger, because they survive and multiply in the circumstances here con-

sidered. In short, we fall back upon statistics, and draw such conclusions as they justify, the details being too minute and numerous to be traced individually. Very much in this way, where we find the population of a State increasing, we conclude that the births and immigration together outweigh the loss by death and emigration. But the loss may be greater in one or more of the townships, nevertheless.

**78.** This is an instructive sample of the order in which steps are taken in Physics, leading to better insight. At first no connection appears between two unquestioned facts: (1) solids cohere and adhere; (2) they dissolve and diffuse. But cohesion and adhesion, on the larger scale accessible to our senses, are naturally regarded as aggregate results. The strength of a steel bar, or of a soldered joint, is a sum of minute contributions, made by a multitude of resistances to tearing asunder, that are furnished *simultaneously* by pairs of particles adjacent to each cross-section. A piece of any solid material can be separated into parts by overcoming such resistances *successively;* this is done in sawing wood, and filing iron, for example. The same mode of stating the facts, however, can be made to include the case of a dissolving solid, without introducing any new idea, so soon as we have discovered cohesion in liquids, and adhesion between them and solids. So long as a solid continues to dissolve, the cohesion of one particle after another is giving way successively — under the stronger attack of some neighbor in the solvent. And the particles of solid, being once set adrift in the comparative freedom of the liquid state, are at liberty to thread their way to all parts of the vessel; deviously, but without permanent interference.

Following up this thought, a glimpse can be had, even, of one reason why the process of diffusion always works out into equality of distribution, although the movements of the individual particles might be describable as wandering and aimless, toward all directions without preference. Let the diagram (Fig. 37) represent a vessel containing three layers of a solution, *A* being more concentrated than *B*, and *B* than *C*. *Providing that the chances are otherwise even*, a larger number of solid particles would cross the lower boundary from *A* to *B* than from *B* to *A*, simply because more solid particles are present in *A*. But balance would ensue when the concentrations in *B* and in *A* became equal; a similar idea applies to *B* and *C*.

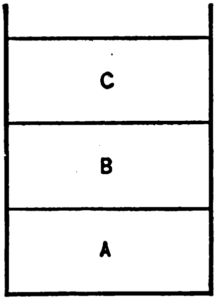

FIG. 37.

Notice the line of these suggestions as regards the internal condition of a homogeneous solution of solid, liquid, or gas in liquid. Is it that each portion is composed permanently of the same particles? Or that conditions remain stationary, while equal numbers of similar individuals are gained and lost (see § 71, end; § 69, end)?

We have thus advanced one or two steps toward a more satisfying view of the phenomena known as solution and diffusion, and of the internal condition of fluids, mainly by arranging ascertained facts in a new perspective. If we avoid the attempt to *account for* cohesion and adhesion, the words themselves are not tinged with theory. They denote such clinging together of like or unlike particles as we unquestionably experience when we try to separate larger groups of them.

## OTHER ACTIONS AT SURFACES OF CONTACT

**79.** While a solution is forming, the layers at the boundary between different substances are evidently a region of decided activity, and not merely inert geometrical surfaces. The same lesson is enforced by other physical phenomena appearing at or near a contact surface, to which we shall next give our attention. The adjoining parts are the seat of active processes, not only when solids are in the presence of some solvent, but also when they are surrounded by certain gases, which their surface layers are found capable of condensing and absorbing in large quantities (Ex. 48). Many fine powders are thus able to counteract the expansive tendency of particular gases, and collect a special gaseous "atmosphere" round the solid particles. It is true of cultivated soils, for example, that the condensation of gases may go to the extent of affecting the nutrition of plants. Hygroscopic [1] substances exercise a strong influence of this nature upon the water-vapor that forms part of our atmosphere; they absorb it, and may remove it almost completely (Ex. 49). Their action can be utilized in "drying a gas," as it is called; that is, in purifying air or other gas from water-vapor. Two gases are sometimes brought into such close relation by condensation in the pores of a solid that combustion ensues (Ex. 50); and in a less violent form, similar consequences accompany the absorption of gases by charcoal, upon which its use as a disinfectant depends. In order to bring about these results, the solid need not always have a visibly open or porous structure (Ex. 51).

[1] Notice the etymology of the word.

## CAPILLARITY

**80.** In general, a homogeneous liquid exhibits no preference for one special arrangement of its parts, except that their weight carries them to the lowest position allowable under the conditions that exist. But the same liquid which is manifestly neutral as regards retaining any internal arrangement produced, for example, by stirring, can be observed to enlarge or contract its boundary, seeming to seek or avoid some particular kind of contact (Ex. 52). Here the mercury retreats from the inner walls of the glass tube, diminishing the very contact which the water increases by rising in the tube. In both cases the liquid changes its original shape, so as either to contract or to enlarge the area of that contact, and disfigures its horizontal free surface in doing so. Traces of similar deformations in the free surface can be detected where liquid touches the walls of a larger vessel.

Now we know that glass does not repel either water or mercury, but adheres to both of them (see Ex. 47); yet these adhesions can be overcome, of course, by stronger influences, or even prevented from appearing. With regard to mercury, especially, it is a question of identifying any effectively stronger influence as the cause of what is seen in the present circumstances. In the first place, when a U-tube of glass contains mercury, notice what determines in which arm the level is higher. It is not the inside diameter of either arm separately, but the *comparative* bore of the two arms. Mercury may be (apparently) either pushed down or drawn up in tubes of the same size, according to the diameter of the tube forming the other arm (Ex. 53). Where a narrow tube is inserted

into a vessel containing mercury (see Ex. 52), the space between them is equivalent to a wider tube.

Secondly, it is clear that those parts of the slender column in $A$ (Fig. 38) which are transferred to the arm $B$ of larger cross-section, become on the whole remoter from contact with glass, and more nearly enclosed among particles of mercury, as the dotted lines of the diagram indicate. Therefore it can be stated that the actual movements so apparent in these instances favor cohesion-contacts of mercury, at the expense of adhesion-contacts between mercury and glass; and it was pointed out in § 76 that the former is the stronger joint. Evidence is furnished by other phenomena, too, that the cohesion-forces of mercury are *effective* in breaking the weaker contacts of that metal with glass. Observe the globular shape assumed by small portions of mercury when lying on a horizontal glass plate. The liquid gathers itself away from the glass repeatedly, after being forcibly flattened into contact with it (Ex. 54). Where the weight involved is relatively small, it does not deform the drops noticeably, and there is close approach to a spherical figure. It is a known property of the sphere, that it exceeds all other solids in the ratio which its volume bears to its surface; and this means that its parts have proportionately more contacts among themselves (within the volume), and fewer with the surrounding region (at the surface). Consequently,

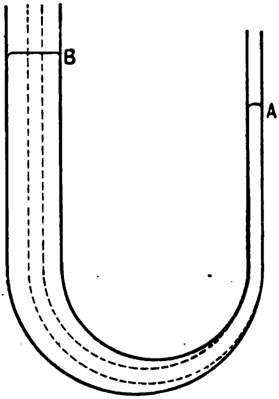


FIG. 38.

when the drops return to their spherical form, they exhibit the preponderating tendency of their particles toward association with each other by preference.

Further insight into the details of the process is beyond our scope here; but we can see that the way is really opened to account for the behavior of mercury in contact with glass, so far as to include it among the instances of stronger action (cohesion) prevailing over weaker (adhesion). In dealing with larger bulks in tubes, the displacement of level is always such that the balance turns in favor of cohesion, though the results are modified by the greater weights of mercury affected, and some other circumstances.

**81.** The next step is to examine whether the same idea gives a reliable clew to the displacements of level that occur when water is in contact with glass, and to other related phenomena.

Is the cohesion of water greater or less than the adhesion of water and glass? When connected glass tubes of different bore contain water, does the difference of level produced favor the stronger action?

Observe the forms assumed by drops of water on (clean) glass, and by drops of mercury upon amalgamated zinc (Ex.). The relative magnitude of the cohesion and adhesion in each case is known (see § 76). Could you predict the present results?

If the drops of a liquid flatten out and wet a solid, would you expect the liquid to be raised or depressed in a narrow tube of that solid, as compared with the general level? Is your expectation in harmony with the facts, when water, alcohol, kerosene, or turpentine is in contact with glass, cube-sugar, or a lamp-wick (Ex.)? Do you

know of any substance toward which mercury acts as these liquids do toward sugar?

Notice that water and mercury can be separated (*i.e.* mercury can be dried) with blotting-paper. Are you able to connect that fact with the discussion of the preceding section?

**82.** Many of these results and similar ones are familiarly spoken of as due to "capillary forces," and the general subject is referred to as **capillarity** (see § 66, foot-note). The latter term is convenient where a name is needed for this group of related phenomena; but the notion of *special* capillary force, acting only under these particular circumstances, is superfluous, like that of "suction force" in pumps. The so-called suction is, as we know, really a *push* due to excess of air pressure on one surface. The characteristic effects included under capillarity are here traced to the same forces of cohesion and adhesion that we have met elsewhere. They produce "capillary phenomena" in settling into new adjustment, after a previous condition of balance has been disturbed.

When the solid is held firmly while the liquid is in contact with it, the approach or retreat of the latter, which we have been observing, is the only movement allowed during the readjustment between cohesion and adhesion. But different consequences of such readjustments appear, where the arrangements permit other forms of freedom to move. It remains to notice a few typical instances of this kind, and to interpret their results.

Two pieces of glass can be drawn tightly together by a thin film of water between them. What part do cohesion and adhesion play in producing this effect? If the pieces of glass were fastened together with (solid) cement, would

you recognize any essential differences between that condition, and the action in the film of water?

In the four following cases (Ex. 55), observe that two objects are also drawn together by liquid films adhering to them. The effects of cohesion show more plainly where the weight is small. The film contracts in every case (except the first), and expresses in this way the tendency of the cohesion-forces to increase the ratio of volume to surface, and thus approach as closely to the condition of the sphere as the circumstances admit.

When the bulb of Experiment 55 (1) is immersed more deeply, what other force balances the excess of buoyancy? In finding specific weight with a hydrometer (Fig. 6, § 31), how will "capillarity" influence the observed result?

What conclusions can you draw from the behavior of the loop of thread: (1) about the relative effort to contract of a film of alcohol and one of soap-water? (2) about the comparative pull on different parts of the thread?

Does the pressure within a soap-bubble confirm or contradict the general line of thought in these sections (Ex. 56)?

What part does "capillarity" play in the manufacture of small shot?

If the barometer reading is affected by "capillarity," is it made larger or smaller than the true value? How may this error be avoided in the siphon barometer (Fig. 29, § 61)? The effect in question is less than 0.05 cm. in any glass tube 1 cm. in clear diameter or larger.

Why should wetting a sail make it "hold wind" better?

How is it possible for a basket woven with fine meshes to hold water without leaking?

For further suggestions see Reference 13.

# HEAT AND ENERGY

## CHAPTER V

### HEAT-QUANTITY AND HEAT-INTENSITY

#### PRELIMINARY

**83.** Many common operations upon the materials of everyday life make us familiar with the process called "heating," and with some effects of it. Water boiled upon a stove goes off as steam; ice turns into water under the influence of sunshine. Brick and pottery are baked in kilns; glass is formed from its ingredients in the melting-pot. Gas is obtained from coal, and lime from limestone, by heating. Iron is made soft in a forge before being hammered into shape. Iron, type metal, silver, are melted with the aid of furnace-fires, and then cast in moulds. Tires and other rings of iron or steel are heated, in order that they may be "shrunk on," and fit very tight.

Various consequences of heating substances can be identified in these typical examples, which suggest several of the general headings to be taken up later. As effects of heating instanced in the preceding list we can name at once: —

(1) To make bodies "hotter."
(2) To change the volume occupied.
(3) To change from one physical state to another.
(4) To form and break up chemical combinations.

These four items mark off an outline of so many groups of phenomena to be considered, whose details it is the purpose of following chapters to supply. Beginning with the first heading, a preliminary inquiry is to be made about the meaning carried by the words "heat," "hotter," "colder." We shall be able to point out some ideas that the current statements about the facts imply, after looking carefully into a few matters of ordinary information. We deem it worth while to put two of those ideas before us in clearer expression; for it is found, in the present case, that a cue can be taken from the "common-sense view of things," as a starting-point for the order and system of more scientific description.

## HEAT AS A QUANTITY

**84.** In connection with any such operations as those mentioned above, a strong and natural suggestion is always felt, that some kind of transfer to the substance is going on continually, so long as it is being heated. And, accordingly, when the reverse process of cooling takes place, the body is almost instinctively regarded as losing what it had gained previously. In one of its accepted uses, the noun "heat" signifies that which is thus supplied or lost; so that we think and speak of gas-flames, fires, the electric arc, sunshine, etc., as **sources of heat.** In the same sense, any heated body, while it is cooling, may become a source of heat for objects in contact with it or near at hand. No reason has been discovered for putting aside this interpretation of the two processes — heating and cooling. Heat is recognized in Physics as something which can be transferred in measured amounts back and

forth among bodies, and which produces in them several definite forms of effect by its addition and subtraction. This is one fundamental idea adopted from the popular conception of the phenomena. The circumstances of heat-transfer, and the consequences of it, as well as the measurement of heat-quantity taken in or given out, are important subjects to be discussed in detail presently.

## INTENSITY OF HEAT

**85.** The second idea drawn from common observation and utilized is that sources of heat differ widely as regards intensity of condition. Experience is within easy reach, which conveys the lesson, and shows how differences of intensity can be brought about. Even the term "intensity" conforms to ordinary usage in speaking of "intense heat." The appliances for heating introduced in various widespread manufacturing processes carry us through a long range of intensities, culminating in the "white heat" of blast-furnaces and the electric furnace. More familiarly still, we know that the fire in a stove is controlled by means of dampers, and allowed to burn more or less fiercely. And, not to neglect entirely the lower end of the scale, we find water producing different results, according as it is warm, hot, or very hot. The action of the bellows in a forge is to make the fire temporarily hotter. In like manner, the flames of gas and alcohol are intensified as sources of heat with the blowpipe employed by jewellers, chemists, and mineralogists. Another instance where great intensity is secured is the portable blast-lamp burning gasoline or kerosene, that is used by plumbers and in laboratories. Keeping these matters in mind, we can

appreciate the need of some basis for comparing heat-intensities. The considerations next to be brought forward will help us toward understanding how this comparison is to be made; and that is a step in the direction of estimating or measuring changes of intensity.

**86.** One distinct impression of intensity in a source of heat is gained through special nerves in the skin, which are stimulated by transfer of heat to or from them. As a piece of iron, for example, is heated, it becomes capable of producing in us a peculiar sensation with increasing sharpness. The result is then habitually referred to additional intensity of condition as regards heat in the metal; we say it has grown hotter. To a certain extent, we can gauge its progress up the scale of intensity by the growing vigor of our own feelings on coming into contact with it. A similar strengthening of sensation caused by water and other substances can be observed after supplying heat to them. On the other hand, the objects touched may be in such a condition that the skin gives up heat, and is felt to be cooled; they are then judged colder than ourselves.

Roughly speaking, our sensations of this character are more vivid, when the local transfer of heat between our skin and other bodies is more rapid. In other words, a more energetic process of transfer accompanies a greater difference of intensity at the surfaces in contact. There are, indeed, obvious limitations upon using the hand as an indicator of comparative heat-intensity; cases like red-hot metals impose the necessity of procuring some substitute. Moreover, our feelings are not to be trusted as scientific standards. The sensations of different persons are not expressible in terms of any permanent unit like the centimeter, the gram-weight, or the second, which we

have adopted in order to compare lengths, or weights, or times. And the judgments of the same person about his sensations on different occasions are apt to be biassed by various circumstances (Ex. 57). But after making all necessary reservations of this sort, the clew suggested by our personal experience has been retained, and followed with advantage for the purposes of Physics. It has been accepted as true regarding the observed spontaneous (or "automatic") transfer of heat: —

(1) That its direction is from higher intensity to lower (from "hotter" to "colder"), and that it ceases only when intensities become equal.

(2) That it proceeds more rapidly when the difference of heat-intensity is greater, — provided that other conditions are parallel. This is one example among several, where a stronger tendency to equalize states accompanies a wider difference between them.

In agreement with the first statement, the greater intensity is ascribed to the body that is found to lose heat, when a transfer of heat has been detected by any method; and when heat-transfer proves to be absent, under conditions known to favor the process, the conclusion is that we are dealing with a case of equal intensities. Therefore, the *direction* of the heat-transfer depends upon which intensity is greater — and upon nothing else. But other elements enter in fixing the *rate* at which transfer goes on; and the proviso introduced in the second statement reminds us to take account of them. Standing in front of a fire, one grows warm faster close by than at a greater distance. It is true, too, that the material is a factor in determining the rate of transfer, as we shall see in due time.

**87.** The two rules just given only summarize universal experience, which forces us to realize that active measures are needed, if some objects are to be kept hotter or colder than others in their neighborhood, and that the necessary precautions become more elaborate, when great differences of intensity are to be maintained. This experience is our rules put into other words.

Where "warming up" or "cooling down" is to be retarded, we value fire-brick, asbestos, felt, sawdust, because they obstruct and delay the spreading of heat, out of a furnace, into an ice-house, etc. Collect a number of such illustrations, showing that application of other materials.

In order to compare heat-intensities, our direct sensation of that quality being thrown out as not entirely trustworthy, some other kind of result must be chosen, by means of which the presence or absence of heat-transfer can be made known. The test will be better suited to its purpose in proportion as it is: (1) reproducible at all times and places; (2) capable of showing minute differences of intensity. In the next chapter we shall consider one effect of heating that meets these requirements reasonably well, and thus take the next step toward *measuring* heat-intensity, by arranging bodies definitely in a series, as hotter or colder.

# CHAPTER VI

## CHANGE OF VOLUME BY HEATING. THERMOMETERS

**88.** Among other consequences that accompany the changes of intensity caused by heating or cooling a body, the alterations of volume produced are prominently noticeable. These expansions and contractions serve so well as an index to mark for the eye any variation of intensity which occurs, that the choice falls upon them very generally, when we seek an "impersonal" standard for that purpose. This constitutes a special reason for the early consideration of changes in volume as one effect of heating; they are evident in liquids, solids, and gases, and are to be discussed deliberately for each of these physical states. Liquids head the list, because they are used most frequently to indicate changes of heat-intensity; and we open with a familiar instance.

The free surface of mercury that is contained in an uncovered glass vessel, and heated over a gas-flame, rises in the vessel as the intensity (judged by sensation) increases (Ex. 58). The change of level is progressive, becoming greater as the mercury is felt to be hotter; it can be made to disappear by cooling; and these results may be repeated at will. The vessel being so contrived that it is possible to trace with the naked eye the movement of the mercury surface, each particular position of it can be associated with a definite condition as regards heat of the

vessel and its contents. And we have secured an instrument that announces its internal changes (of heat-intensity) by external signs (movements of the mercury thread), visible and interpretable for all observers alike. The lengthening and shortening of the thread are direct evidence of variations in the instrument's own condition by transfer of heat to it or from it. The essential features of the ordinary mercury thermometer are recognizable here.

## THE THERMOMETER

**89**. Alcohol or water can be substituted for mercury without altering the general character of the phenomena (Ex. 59), so long as the range of heating and cooling is not extended too far. In all three arrangements the inside volume of the glass vessel is enlarged by heating (Ex. 60). But that increase is less in amount than the change of bulk in the liquid; hence the free surface of the heated liquid rises *in the heated vessel.* The result that is utilized in the mercury thermometer is the excess of mercury-expansion over the added capacity of the glass envelope. This is known as the "apparent expansion" of mercury (in glass). The mercury-in-glass thermometer shall be called **thermometer** for brevity.

When thermometers are made, they are usually sealed air-tight, and the space beyond the mercury thread is a vacuum. Can you see any weighty reason for contriving this so? Can you devise any simple way of obtaining the vacuum?

What other effects besides expansion do you find, if the heating of water or alcohol is continued? If the cooling of water is carried too far, what phenomena appear, besides

change of volume? Do you see in these facts any grounds for preferring the (mercury) thermometer?

**90.** But thermometers are not limited in use to indicating whether they have themselves become hotter or colder; nor is their purpose qualitative merely; they are measuring instruments. We must examine what it is that they serve to measure, and learn how to interpret the "degrees" of their scales. This word is employed, popularly as well as scientifically, when thermometer readings are given as numbers. And, though it has, of course, nothing to do here with circular measure, the sign for angular degrees (°) is nevertheless added.

If we inspect an ordinary thermometer-scale, its intervals (degrees) are seen to be equal. Supposing the tube containing the mercury thread to be of uniform bore, the volumes of mercury lying between any two consecutive marks of the scale are equal also. And when the end of the thread moves through one degree, the (apparent) expansion of the mercury is equal at all parts of the scale. Now the observed volume-changes are to be translated into intensity-changes; and in order to do this, some relation between the two must be established. It has been agreed, therefore, as a first basis, that we will accept equal volume-changes on the same thermometer as corresponding to — and denoting — equal intensity-changes. Consequently, the degrees on such thermometer-scales are intended to mark off equal steps of intensity; and in this connection with intensity the appropriateness (such as it is) of the word "degree" becomes more evident. Its meaning here is parallel to that in the phrases, "high degree," "low degree," "intense degree."

Primarily, the degree is a step of intensity for the ther-

mometer itself; but then, secondly, any thermometer may record on its scale the heat-intensity of some other substance or object in contact with it, after the conditions of the two have become equalized by transfer of heat. Indeed, the practical utility of the thermometer in the arts, in common life, and in scientific work turns mainly toward letting us know "how hot" or "how cold" *other* things are; the air within a room, or an oven, or the chambers of a fruit-drier, or an incubator; the water of the ocean or of a bath; a sugar-syrup, or a nickel-plating solution.

## SCALES OF THERMOMETERS: FIXED POINTS

**91.** The first thermometers did not contain mercury, and on any one of them the steps of intensity were not what we should now call equal. The starting-points of their scales, too, were chosen at random, and there was no general agreement about the intervals or degrees (Ref. 14). Thus the scale of each thermometer was unique; the readings of one conveyed no definite meaning in terms of any other. Some time elapsed before successive improvements gave us the present thermometer-scales, which are made (it is well known) on a uniform plan; or, at least, on one of three accepted plans, which can be translated easily, each into terms of the others. We can all appreciate how time and trouble are saved in the intercourse of civilized countries, by adopting international units for lengths, volumes, and weights. And it is clear that the same sort of advantage is secured by establishing a common measure of other quantities, like heat-intensity, with which the whole world is concerned. This thought explains the effort to contrive a uniform scale for thermometers which

was made promptly, and which met with fair success at a comparatively early date. It is worthy of remark, in this instance and elsewhere in Physics, how much careful attention has been devoted to making instruments of the same type *interchangeable.* This involves, first, that we agree upon convenient standards of measurement, and, secondly, that we apply them consistently in graduating (calibrating; see § 24) the instruments. What the plan is, according to which thermometers are graduated, must next be made clear. We shall begin by explaining how the numbering of the scales is arranged, because that happens to be a more essential matter than the length of the degrees.

**92.** Whenever a thermometer is kept among pieces of clean melting ice in an open vessel, it is found to reach the same state of heat-intensity, and to maintain that condition permanently. Another definite intensity is attainable by hanging the thermometer in steam given off by boiling water; and this, too, can be preserved continuously, so long as the pressure exerted by the steam is constant (Ex. 61). A third intensity, also fairly definite, is shown when a thermometer bulb is held in the mouth of a person in good health. Such physical conditions as those named are favorable for the adjustment of a thermometer-scale, because they can be reproduced with very few special appliances, and at almost any place. After trying several similar expedients, the first two conditions mentioned (melting ice and steam) have been adopted universally as standard states of intensity. Change of steam pressure affects the second visibly (Ex. 62), so that must be located more closely by specifying a particular pressure for the steam; one atmosphere (see § 52) has been selected as the

standard pressure. Allowance is then to be made properly for any excess or defect in the steam pressure at the time of actually marking this point on the scale. The two standard intensities will be spoken of as the **ice-point** and the **steam-point** of a thermometer. These are the so-called **fixed points** of the graduation.

**93.** The thermometer-scales still current among civilized nations are of three types, all using the same fixed points, but differing among themselves in two respects: (1) in the number assigned to the ice-point; (2) in the subdivision of the interval between the ice-point and the steam-point. The three scales are known as the Fahrenheit scale, the Centigrade (or Celsius) scale, and the Réaumur scale. The following table exhibits them comparatively; and in it is included the third standard intensity — the "blood-heat" of our house thermometers. This is as constant and well ascertained (on the average) as the steam-point, unless a barometer reading and the "correction for pressure" are available.

THERMOMETER SCALES

| Intensity | Fahrenheit | Centigrade | Réaumur |
|---|---|---|---|
| Ice-point . . . . | 32° | 0° | 0° |
| Steam-point . . . | 212° | 100° | 80° |
| In mouth . . . . | 98°.6 | 37° | 29°.6 |

The Fahrenheit and the Centigrade scale are found side by side among English-speaking people; but the latter is adopted almost without exception for scientific records — in all countries. The Réaumur scale is relatively less

important than the two others, its use being both popular (or "domestic") and limited.

Will the *length* of a degree (in centimeters) be the same for all thermometers whose scales are of the same type?

What is the main reason why the cross-section of the thread is chosen small in comparison with that of the bulb (see requirement (2), § 87)? Can you add any second reason?

Express rules for finding the reading on each thermometer-scale, corresponding to a given reading on either scale of the other types.

## TEMPERATURE

**94.** The foregoing description of their origin must make it plain that all three thermometer-scales are *arbitrary;* that is, each depends upon conventional agreement alone for the location of its starting-point or zero, and for the number of degrees between the ice-point and the steam-point. The scales differ from each other, but they stand on an equal footing in this respect; none of them gives us by its reading a numerical measure of intensity. The reading "0°" cannot mean absence of all heat, since thermometers out-of-doors on a cold winter day are known to indicate 25° below zero (Centigrade or Fahrenheit); and, in those circumstances, before they can be brought to read zero, they must be warmed, and have their intensity increased.

Thermometer-scales, then, show only *differences* of intensity; and even the step of intensity spoken of as a degree changes in amount as we pass from one type of scale to another. Such readings of intensity-difference are called **temperature.** Hereafter in this book, we shall

use the Centigrade scale exclusively, when temperatures are to be recorded numerically. The Centigrade temperature observed on a thermometer measures the difference of heat-intensity between the present condition of the instrument, and its condition when surrounded with melting ice. Recollect that the unit of this measurement (the degree Centigrade *of intensity*) is constant in all thermometers, though the length of the degree (in centimeters) may vary within wide limits (see § 90, § 92).

**95.** The relation between intensity and temperature is like that existing between the distance from the earth's centre to a given place, and the height of the latter above the sea-level. We can deal with differences of level, and yet be entirely ignorant how far off the earth's centre is; so we are able to measure or record differences of heat-intensity numerically as temperatures, although we are without experience of bodies having *no heat* in them. And further, just as the ocean carries a nearly constant level along its entire shore-line, from which we can start in measuring vertical heights (elevations), so a uniform zero for temperature is available as a point of departure, wherever melting ice can be obtained.

It lies in the very nature of this relation, then, that greater heat-intensity is read as higher temperature, and that equal temperatures mark equal intensities — on any scale. Consequently, a thermometer will gain or lose heat, according as the body concerned with it in a transfer of heat is of temperature higher or lower than its own (see § 86). The process ceases when the two temperatures reach a common value, which the thermometer enables us to read off. In this way we find "how hot" a body is by means of a thermometer.

**96.** The plan announced in § 88 involves a study of expansions and contractions in connection with changes of temperature, for substances in the liquid, the solid, and the gaseous state. In executing that plan experimentally, it becomes necessary to observe the temperatures of those substances at various stages of the heating or cooling, in terms of the thermometer-scale that is now at our disposal. But the temperature of a thermometer may be influenced by objects at a considerable distance, as well as by those in contact with it (Ex. 63). Such influences are not confined to hotter bodies, — they may proceed from those which are colder; the proximity of an iceberg is often signalled by a decided fall of temperature on board a ship. Hence we must assure ourselves that disturbing influences from other sources are practically excluded under the working conditions, when we "take the temperature" of a particular object with a thermometer. Otherwise the mercury thread may become stationary, without equality of temperature between that object and the thermometer.

What fact is really registered when the thread of a thermometer neither lengthens nor shortens?

## COEFFICIENTS OF EXPANSION FOR LIQUIDS

**97.** In considering the changes of volume produced in liquids by heating, the question is to be asked: Do they expand all alike, or some more and some less? There would be no satisfactory basis for comparison, if mere increase of volume in cubic centimeters were measured, no reference being made to the original volume of the liquid, or to the range of temperature within which the expansion occurs. For instance, definite conclusions could not be drawn by comparing a pailful of water with a glass-

ful of kerosene in this respect, especially if the latter were raised in temperature more than the former. In order to remove such elements of vagueness, equal volumes of two liquids are taken; or the observed results are reduced by calculation to a basis of equal volumes. And similarly with temperature intervals; either they are actually the same, or they are equalized by calculation before comparison is finally made (Ex. 64).

The usual method of preparing observations for record in terms of *equal* volumes and *equal* changes of temperature expresses, for each liquid, the expansion corresponding to *unit* volume (1 c.c.) and *unit* change of temperature (1° Cent.). All things considered, that form of comparison proves to be simplest and most advantageous; an example affords the readiest explanation of how the plan is worked out. Let a portion of some liquid be taken, whose volume at 10° is 150 c.c.; and suppose that the volume becomes 153 c.c. on raising the temperature to 70°. Then the expansion is $153 - 150 = 3$ c.c. But each cubic centimeter of original volume contributes its quota to the result; so the expansion for one cubic centimeter is $\frac{3}{150} = \frac{1}{50}$ c. c. And the actual rise in temperature being $70° - 10° = 60°$, the (average) expansion reckoned for one cubic centimeter and one degree would be

$$\tfrac{1}{50} \div 60 = \tfrac{1}{3000} = 0.00033 \text{ c.c.}$$

When the experimental data have been reduced to these terms, we obtain what is called the **coefficient of expansion** for volume. If we find this coefficient for mercury entered as 0.00018, it means that 1 c.c. taken at 10° and raised to 11° will occupy 1.00018 c.c. The extension to any given volume and change of temperature follows without diffi-

culty. Suppose, for instance, that a portion of mercury is measured as 750 c.c. at 15°. The volume occupied by it at 90° would be 750 (1 + 0.00018 (90 – 15)) c.c.

The same ideas may be conveyed more generally, and in a compact algebraic formula. Denote the original volume of liquid by $V$, the increased volume by $V'$, and the rise in temperature by $R$. Then we find,

$$\left.\begin{array}{c}\text{Coefficient of Expansion}\\ \text{(Volume)}\end{array}\right\} = \frac{V'-V}{V} \div R = \frac{V'-V}{VR}. \qquad (7)$$

**98.** In the table below, coefficients of expansion for a few common liquids are quoted. They represent true (not apparent) expansions, which must be regarded as *averages*, because the coefficients show slight differences at high and at low temperatures. The figures are confessedly approximate, however, being intended mainly to give evidence as to the range of values for various liquids, and thus answer the question that heads § 97. Although such variations exist as appear in the table, liquids are alike, as a general rule, in one respect. They expand when their temperatures are raised, and contract only while their temperatures are falling. The single exception to be noted as practically important is found in the case of water, concerning which special mention is reserved for another paragraph.

COEFFICIENTS OF EXPANSION (LIQUIDS)

| | | | |
|---|---|---|---|
| Water . . . . . . | | Ether . . . . . . . | 0.0015 |
| Alcohol . . . . . | 0.0011 | Olive oil . . . . . . | 0.0008 |
| Mercury . . . . . | 0.00018 | Turpentine . . . . | 0.0007 |
| Glycerine . . . . . | 0.0005 | Petroleum . . . . | 0.0009 |

Make the necessary measurements, and calculate the average coefficient of expansion for water, between 15° and 60° (Ex. 65). Does your method yield true or apparent expansion? However that may be, enter your result in the table. Numerically the difference is small, and can be neglected here.

## LIQUID EXPANSION: ILLUSTRATIONS

**99.** As a matter of experience, do you find that a thermometer surrounded by liquids like water, alcohol, or kerosene, in glass or metal vessels, is shielded from other influences, which would transfer heat to it if the liquid were not present (Ex. 66)?

Do you detect any differences of temperature among the parts of a liquid that is heated from below? Do the currents that are observable (Ex. 67) tend to remove such differences, or to produce them? Connect the origin of these currents with the ideas of § 33. How does stirring aid in making the liquid homogeneous?

Why must changes of temperature be guarded against, if the phenomena of diffusion in liquids are to be shown?

At 0°, the weight of 1 c.c. of mercury is 13.60 gr.-wt. If mercury is raised to the temperature 30°, how much does 1 c.c. of it weigh?

The method of Experiment 29 or Experiment 31 (§ 62) is applied in determining a true expansion-coefficient. Both tubes are filled with the same liquid, but a constant difference of temperature is maintained between them (Ex. 65, Ref. 15). Explain the main idea of the plan.

Which is greater, the specific weight of alcohol (referred to water), both liquids being at the temperature 15°, or

its specific weight when the comparison is made at 40°? Does Experiment 64 supply the answer to this question? If we accept the expansion in the table for alcohol, and your own number for water, will the two specific weights differ by as much as one per cent?

What two temperatures must be noted, if we are to understand more exactly what is meant by saying, "The specific weight of turpentine is 0.87"?

With really equal atmospheric pressure, the barometer height will be greater on a hot day than on a cold one; show why this is true (see § 48). Does the effect depend upon *apparent* expansion? Where accurate barometer heights are required, therefore, the temperature of the mercury is recorded. A standard temperature has been agreed upon, — which is regularly zero Centigrade for this purpose and several others, — and allowances being made finally for departures from it, the "Correction for temperature," or "Reduction to zero" is introduced into the barometer reading.

At the temperature 25°, the mercury levels in a siphon barometer are 75.5 cm. apart vertically. What would this distance become if the mercury were cooled to zero, the atmospheric *pressure* remaining unchanged?

**100.** Water has been alluded to already as an exception among liquids, in not expanding at all temperatures when heated. Water begins by contracting, if we start at 0° and supply heat (Ex. 68). The temperature 4° is very closely that at which the contraction ceases; beyond that point expansion sets in, and continues as the temperature is raised. This peculiarity of water is confined to a narrow temperature interval, but it has momentous consequences, nevertheless.

Suppose that a larger body of water — a lake or a deep pond — is cooling quietly in winter, from the free surface downward. The distribution of temperatures at different levels may be somewhat like that represented in the first diagram (Fig. 39) before the process begins.

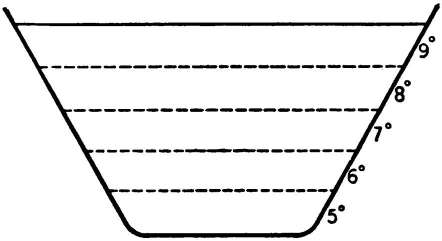


FIG. 39.

This is so far a *stable* arrangement, each lower layer being specifically heavier than all those above it. In later stages the arrangement ceases to be stable; the top layer is specifically heavier than those below; the parts of it force their way down. The circulation that ensues tends to reduce all the water to 4°, the temperature of greatest specific weight (Fig. 40).

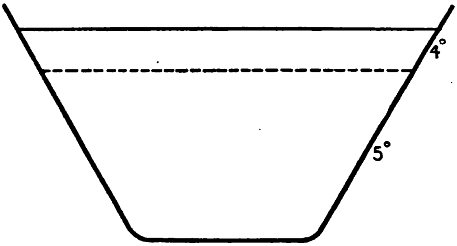


FIG. 40.

Provided that the cooling is continued, a third stage is reached (Fig. 41), which is again stable; and its general character can be preserved until the temperature 0° is produced at the surface. If that con-

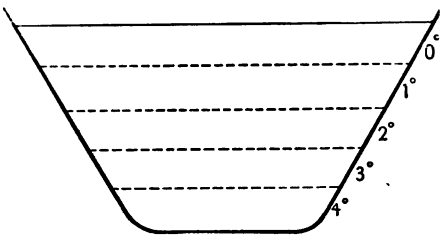


FIG. 41.

dition is maintained, ice will form there; recollect that zero Centigrade is the melting-point of ice, and also the freezing-point of water.

When the metric system was planned, the intention was that 1 gr.-wt. should represent exactly the weight of 1 c.c. of water at 4° Centigrade (see Ref. 4). More precise measurements of recent date show that the relation was missed by about 13 parts in 1,000,000, being more nearly fulfilled at 3° *and* at 5° than at 4°. Does 1 c.c. of water at 4° weigh more or less than 1 gr.-wt.?

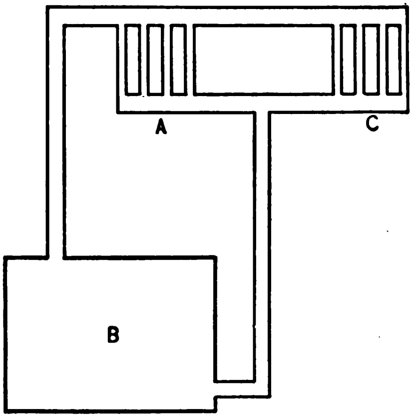


FIG. 42.

The following numbers may prove useful in calculating the weights of water volumes within the range of atmospheric temperatures; they are correct to 1 part in 1000: —

| TEMPERATURES | WATER: GR.-WT. TO 1 C.C. |
|---|---|
| 0° to 12° | 1.000 |
| 13° to 18° | 0.999 |
| 19° to 23° | 0.998 |
| 24° to 27° | 0.997 |

In connection with the diagram of a hot-water heating system (Fig. 42), explain the circulation that carries the

hot water from the boiler *B* to places *A* and *C* where it is needed.

Oceanic currents on a large scale are partly due to similar causes (Ref. 16).

## COEFFICIENTS OF EXPANSION FOR SOLIDS

**101.** Solids as a class, like liquids, expand when their temperature rises, and contract when it falls. The effect is particularly noticeable in metals, but is not exhibited by them alone (see Ex. 60). The behavior of an iron rod is typical (Ex. 69); and many similar results are familiar practically. Rivets are put in place while hot, in order that their contraction on cooling may draw the parts together, and make a tighter joint. Glass cracks in consequence of expansion, if heated locally. Steel bridges must have an "expansion-joint" somewhere, to provide for their changes of length between a cold day in winter, and a hot one in summer. Similarly, a "telescope-joint," or some equivalent device, is required in long lines of pipe, especially if they convey steam or hot water intermittently. Pendulum clocks are found gaining or losing time according to the season of the year, unless the disturbance of their rate is prevented by a special contrivance. The change in passing from winter to summer (caused by expansion) is in the same direction as that produced by lowering the pendulum-bob. Observation will furnish so many illustrations of this property in solids, that it is needless to multiply them here.

Show how a metal rod arranged as in Experiment 69 could be used as a thermometer.

**102.** In every one of the instances named, we can verify that expansion and contraction in some one line are

prominent, rather than change of volume. It is very generally true of rods, bars, wires, tubes, and other bodies of similar form, that heating affects their cross-section less seriously; the more important consequences are accumulated in their longest dimension. In dealing with solid materials, therefore, we are most likely to be concerned with their "linear expansion," as it is called. We measure their changes of size *one way*, or along one line of them.

The general drift of the remarks in § 97, which lead up to the idea of expansion-coefficient for volume, can be transferred so readily and completely to the new type of case, on substituting everywhere length for volume, that we shall not repeat the particulars. The **coefficient of linear expansion**, as applying to any solid, is reckoned for one centimeter of length, and one degree rise in temperature. Let $L$ denote original length, $L'$ increased length, and $R$ the corresponding increase of temperature. Then, imitating the model of Equation (7), § 97, we write in symbols,

$$\left.\begin{array}{c}\text{Coefficient of Expansion}\\ \text{(Linear)}\end{array}\right\} = \frac{L' - L}{L} \div R = \frac{L' - L}{LR}. \quad (8)$$

This may be an average coefficient; in a number of cases linear expansion for an interval of one degree causes additions to the length that are unequal at high and at low temperatures. The expansion is "not uniform," we say. There are a few instances where a solid contracts with increase of temperature, but none of practical importance. The approximate values of the "linear coefficient" for several materials in common use are presented in the table below, from which it can be seen how "individual" substances are in this respect.

COEFFICIENTS OF EXPANSION (LINEAR)

| | | | |
|---|---|---|---|
| Glass | 0.000008 | Lead | 0.000029 |
| Hardwood | 0.000006 | Iron and Steel | 0.000012 |
| Paraffine | 0.0004 | Copper | 0.000017 |
| Sulphur | 0.0001 | Silver | 0.000019 |
| Hard Rubber | 0.00008 | Gold | 0.000015 |
| Brass | | Platinum | 0.000009 |
| Graphite | 0.000007 | Aluminum | 0.000023 |

Make the necessary measurements, and calculate the (average) linear coefficient of expansion for brass, between 15° and 100° (Ex. 70). Insert your result in the table.

**103.** Where materials are to be soldered, welded, or brazed together, they should be selected (when choice is open) so that their coefficients of expansion do not differ widely; otherwise the joint is apt to break or work loose, if it is heated much or frequently. Are the conditions favorable to strength where platinum wire is fused into glass? Incandescent (electric) lamps contain such joints. Plumbers are accustomed to interpose a brass collar *B* (Fig. 43) between iron and lead pipes *F* and *L* that are to be joined with lead or solder. Does this practice improve upon that of uniting iron and lead directly, as regards the effects of expansion by heating and cooling?

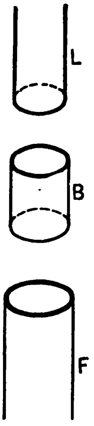

Fig. 43.

A steel bridge having a span of 60 meters is provided with an expansion-joint at one end. How much play is required there for a range of temperature from $-25°$ to $+30°$?

Expansion and contraction affect (more or less) all cen-

timeter scales, and other standards with which measurements of length are made. A meter rule of brass is correct at 0°; what is its error at 20°?

**104.** Sometimes it becomes necessary to think of change in length and change of volume for the same solid body. Then we have to do with two coefficients of expansion — one linear, and the second for volume. But such matters are simplified by remarking that the volume-coefficient is *practically* three times the linear coefficient, because both are numerically small. The relation is easily shown by considering a cube whose edge is originally 1 cm. long, and asking what its volume becomes, when its temperature is raised one degree. Let the coefficient of linear expansion for the substance be $e$. Then each edge of the cube is lengthened to $(1 + e)$ cm., and the enlarged volume is $(1 + e)^3 = (1 + 3e + 3e^2 + e^3)$ c.c. But $e$ is a small fraction of one centimeter, and $3e^2$, $e^3$ are so much smaller that we can drop them out of account in comparison with $3e$. If we do this, $3e$ measures the increase of volume of 1 c.c. for 1°, and is, therefore, the coefficient of expansion for volume; it is three times the linear coefficient, as we see. In order to justify the neglect of $3e^2$ and $e^3$, take the actual numbers for paraffine, which offers the severest test among the substances in the table (§ 102), because its coefficient is largest. We find

$$\begin{aligned} 3e &= 3 \times 0.0004 = 0.0012 = 12 \times 10^{-4}; \\ 3e^2 &= 3 \times 0.00000016 = 0.00000048 = 48 \times 10^{-8}; \\ e^3 &= 0.000000000064 = 64 \times 10^{-12}. \end{aligned}$$

Throwing away $3e^2$ changes the volume-coefficient by only 4 parts in 10,000; and such values are not known accurately enough for that rejection to be of any consequence.

In connection with this instance, notice the convenience of writing very large or very small numbers as powers of ten.

Compare the coefficients of expansion (for volume) obtained from the two lists (§ 98, § 102). Do you find the statement borne out, that the former are on the whole larger?

The fact that the centimeter scale of a barometer expands by heating diminishes the temperature correction of the instrument. What *linear* coefficient of expansion must the material of the scale have, in order that the barometer reading may be correct at all temperatures? If the barometer height is read on a brass scale, is the temperature correction at 25° so large that you need to take notice of it in your laboratory work by reducing the readings to the standard values at 0°?

## COEFFICIENTS OF EXPANSION FOR GASES

**105.** We have now arrived at the point of considering the expansion and contraction of gases by heating and cooling. Here, as in the case of liquids, we can restrict ourselves to changes of volume alone. And, unless accuracy beyond our limits is required, the distinction between apparent and true coefficients disappears; on account of the comparatively large expansion, the variations of capacity in the containing vessels become relatively small.

But gas volumes are not dependent solely upon temperature, as the volumes of solids and liquids so often are, at least practically. Alterations of bulk are the decided response in gases to changes of pressure, as well as to changes in temperature. Consequently, if the effects of varying the temperature are to be studied by themselves,

either the pressure must be kept constant, or the changes in it must be allowed for separately. This forms the counterpart of the condition attached to Boyle's Law, that "the gas must be guarded against becoming hotter or colder while the experiment is in progress"; constancy of *temperature* is one supposition in applying that rule, while constant *pressure* simplifies the situation here (see § 63). This illustrates the common method in Physics, of taking up one element at a time, though many enter into the real circumstances.

What other instances can you bring forward, where considerations connected with temperature add new features to matters that have been treated previously?

**106.** Provided that the pressure remains the same, a portion of air confined at 0° increases its volume almost in the ratio $\frac{4}{3}$ when heated to 100° (Ex. 71); this corresponds evidently to a coefficient of expansion much larger than any we have met in solids or liquids. Similar experiments carried out at various (constant) pressures and with different original volumes are found to yield ratios of the volume at 100° to that at 0° which differ but slightly. This would be naturally expected, perhaps; but a remarkable fact is that the ratio preserves its value when the test is made with any other gas instead of air. The value of the ratio changes with the choice of temperature interval, of course, but it remains nearly equal for all gases whose original and final temperatures are the same. Therefore the nature of the gas plays no deciding part; the same absence of *individuality* is manifested by oxygen, hydrogen, nitrogen, coal-gas, etc., here, that we have commented upon in § 63, § 64, and § 68. For these purposes, each gas seems to behave as though it were just so many particles,

nearly indifferent to one another, and to their neighbors of other kinds. We have the opposite extreme, by way of contrast, in particles of solids and liquids, whose special adjustments in each substance betray themselves in particular values of cohesion and adhesion, and varying rates of expansion, diffusion, etc.

**107.** In consequence of their rapid expansion and contraction, both temperature and pressure must be recorded, when volumes of gas having known weights are observed, in order that the conditions may be fully understood. It is clear that the specific weight of a gas is likewise affected by its temperature, after providing for the reduction to standard pressure (see § 65). Complete definiteness on these points is reached by accepting zero Centigrade as the standard temperature to which volumes and specific weights of gases refer, unless the contrary is noted. Conversion from the actual working temperature to 0° is simple, with a known coefficient of expansion; we shall proceed to express its value.

Write $V(0)$ for the volume at 0° of a given portion of (any) gas; and similarly $V(50)$, $V(100)$ for its volume at 50° and 100°. Then compare the three ratios: —

$$(1)\ \frac{V(50)-V(0)}{V(0)}; \qquad (2)\ \frac{V(100)-V(50)}{V(50)};$$

$$(3)\ \frac{V(100)-V(50)}{V(0)}.$$

Judging by your experimental results, which of them have most nearly equal values? With a solid or a liquid, $V(0)$ and $V(50)$ would differ so little, that the quotients in (2) and (3) would be practically identical; but their difference is perceptible for a gas.

Expansions like the numerators of (1) and (2) are found equal by experiment, if they apply to the same portion of gas and equal numbers of degrees. Now the coefficients of expansion corresponding to (1) and (2) might be put in the forms (see § 97, Eq. (7)),

$$(1)\ \frac{V(50)-V(0)}{V(0)} \div 50; \quad (2)\ \frac{V(100)-V(50)}{V(50)} \div 50.$$

But the coefficients become equal, and the real uniformity in the expansion of gases is made apparent, if we divide always by the volume at the *same temperature* (like $V(0)$), and not by the volume at the *lower temperature of the interval* ($V(0)$ in one case; $V(50)$ in the other). As a standard temperature for the volume in the denominator, 0° is again adopted. In those terms, the expression for the coefficient of expansion between the lower temperature $T$ and the higher $T_1$ is,

$$\left.\begin{array}{c}\text{Coefficient of Expansion}\\ \text{(Volume: Gas)}\end{array}\right\} = \frac{V(T_1)-V(T)}{V(0)} \div (T_1 - T)$$

$$= \frac{V(T_1)-V(T)}{V(0)(T_1-T)}. \qquad (9)$$

For all gases, the coefficient thus expressed remains practically uniform through wide ranges of temperature, its value being close to $\frac{1}{273} = 0.00366$. This rule is often quoted as a "Law," and connected with the name of Gay-Lussac or Charles (Ref. 17). The deviations from it are more marked in the extreme cases where the gas is approaching the state of vapor. This parallels our experience with Boyle's Law (see § 63).

**108.** What value would the coefficient have, if the standard volume in the denominator were chosen at 15°, and

not at 0°? How would its value be changed if the Fahrenheit scale were used?

An equivalent in words for Equation (9) is: Gases expand uniformly by $\frac{1}{273}$ of *their volume at 0°* for each degree (Cent.). The volumes at $T_1$ and $T$ may therefore be written, if we denote the coefficient $\frac{1}{273}$ by $K$,

$$\left.\begin{aligned} V(T_1) &= V(0) + KV(0)(T_1 - 0°) = V(0)(1 + KT_1), \\ V(T) &= V(0) + KV(0)\,(T - 0°) = V(0)(1 + KT). \end{aligned}\right\} \quad (10)$$

Hence the expansion between the temperatures $T$ and $T_1$,

$$V(T_1) - V(T) = KV(0)(T_1 - T). \qquad (11)$$

If we need to know it, $V(0)$ can be calculated by means of Equation (10).

A volume of gas is measured as 800 c.c. at 17°, when the barometer height is 75.6 cm. What would be its volume: (1) at the same pressure, but at the standard temperature 0°? (2) under standard conditions of both temperature and pressure?

What is the specific weight of air at 20°, and under the pressure read as 75 cm. on the barometer, referred to air at the standard conditions?

**109.** When a portion of gas is heated, it can be prevented from expanding, if the pressure upon it be increased adequately. Where the rules of § 63 and § 107 apply, the ratio of the pressures at any two temperatures, should the gas be not allowed to expand, is equal to that of the volumes at the same two temperatures, if the gas were allowed to expand under constant pressure. This conclusion may be drawn by thinking of the actual result as reached in two stages: —

(1) Heat the gas from the lower temperature ($T$) to the higher ($T_1$), permitting it to expand from volume $V$ to $V_1$. [Constant pressure $= P_1$.]

$$\frac{V_1}{V}=\frac{1+KT_1}{1+KT} \text{ (see Eq. (10), § 108).} \qquad (12)$$

(2) Increase the pressure to the value ($P$) at which the gas is compressed to its original volume. [Constant temperature $= T_1$.]

$$\frac{P}{P_1}=\frac{V_1}{V}=\frac{1+KT_1}{1+KT} \text{ (see Eq. (6), § 63).} \qquad (13)$$

That is, the ratio of the final pressure ($P$) to the original pressure ($P_1$), under the actual condition of constant volume, has the value announced above. It is instructive to carry out these two stages on the apparatus of Experiment 71. The increase of pressure exerted by a confined portion of heated gas is utilized in one form of the **gas thermometer** for measuring high temperatures.

The high pressure inside the cylinder of a gas-engine, or a gasoline-engine, has its origin in the rapid heating of mixed gases there by sudden combustion ("explosion"). The extra pressure due to the raised temperature drives the piston forward.

Starting with 1200 c.c. of air (temperature 15°; barometer height 74 cm.), find by calculation another pair of conditions (pressure and temperature) under which the volume will be the same. Is there only one such pair?

$V_1$ is a volume of gas for the barometer height $H_1$ and the temperature $T_1$; the volume of the same portion of gas is $V$ for barometer height $H$ and temperature $T$. Express in symbols an algebraic relation between $V_1$ and $V$. [Introduce the altered conditions one at a time.]

## GAS EXPANSION: ILLUSTRATIONS

**110.** So long as the atmosphere near the earth's surface in any region is practically homogeneous and at rest, the parts of it show no decided and systematic movement, because their specific weights are equal, and nothing is to be gained or lost by interchange of position. When the temperature is least at the ground, and increases as we go up, the arrangement is stable under constant pressure, since the specifically heavier gas is already in the lowest layer. But if the lower layers have taken up heat from any source, and increased in temperature, the stability is disturbed; the heated portions become specifically lighter, and cannot hold their own against the superior weight (bulk for bulk) of the cooler portions above; they are forced out of the lowest positions. The tendency of a source of heat situated in the lowest part of a vertical column of gas is to set up a circulation that drives the heated gas upward. One way of expressing the effect is to say that the buoyant force exerted by the surrounding cooler portions exceeds the weight of any heated portion included among them. The latter is lifted for the same reason that a balloon "rises" — or more accurately "is raised."

Sunshine converts into active sources of heat those regions of the earth's surface which receive it, and they set up the circulations of the atmosphere upon a large scale that are felt as winds (Ref. 18). The same kind of action is relied upon to produce draft in chimneys, the fire being here the source of heat, and the effective difference of weights being reckoned between the heated products of combustion (mixed with some air) in the chimney, and an equal column of atmosphere out-of-doors.

Is there any reason apparent why a stove should "burn better" in winter than in summer, other things being equal? What advantage can you see in a tall chimney, as a means of producing strong draft? For the same purpose, a blower is used at an open grate; explain its action.

A fire maintained at the bottom of a mine shaft is an efficient device for securing ventilation. If the mine has only one opening above ground, the equivalent of "upcast" and "downcast" is commonly produced by a partition lengthwise of the shaft. The need of this element can be shown on a small scale (Ex. 72). The ventilation of a building can be provided for in the same way, by a fire at the foot of a chimney; the fire in an open fireplace does this service for a room.

In heating houses by hot air from a furnace, also, circulation is produced by difference of temperature. Trace the circulation *of air* in that case, and where rooms are warmed by stoves, or "radiators" supplied with steam or hot water. In order to obtain even temperature at all levels in a room, is it better to introduce the fresh (cold) air near the ceiling, or near the floor?

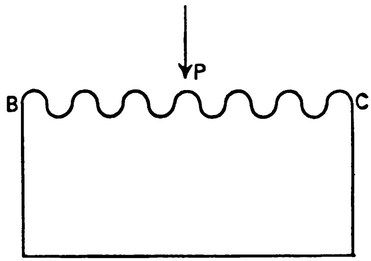

FIG. 44.

**111.** The aneroid[1] barometer indicates changes of pressure by alterations of form in an air-tight metal box (Fig. 44). The cover *BC* is the sensitive part, the other walls being made unyielding. It is thin, springy, and shaped somewhat as shown, in order

[1] Consult the dictionary about the etymology of the word.

that it may "buckle" to a measurable extent, for moderate variations of external pressure. Its slight movements are magnified by suitable mechanism (levers, etc.) and read upon a scale. The aneroid being portable, it is employed in estimating the altitude of mountains (see § 52). Its scale can be calibrated by comparison with a (mercury) barometer; pressures corresponding to greater elevations being produced artificially with an air-pump.

The use of the instrument being to register changes of *external* pressure, the inside pressure should be sensibly constant. To that end, a partial vacuum is produced within the box. Show in what way this precaution reduces false indications due to rise and fall of *temperature*. When the inside pressure corresponds to 10 cm. of mercury on a gauge (see § 59), how many meters of rise from the sea-level would be compensated by a drop from 20° to 10°? [The volume enclosed by the box is supposed unaltered.]

**112.** The tendency of a gas to occupy a greater volume can be resisted with ease, where the temperature is raised several hundred degrees. But it is difficult to prevent entirely the expansion of liquids and solids under like circumstances; or the linear contraction of solids when they are cooled. The reason for this difference lies in the magnitude of the forces involved. The force required to hold a bar down to its original length while it is heated is continually shortening the bar by the amount through which it would expand otherwise (see § 109 (2)). And the compression of solids and liquids by even a small fraction of their length or volume demands enormous forces, as we know. When a tire or ring fits tight while it is hot, it is in some measure prevented from contracting as it cools, and binds the parts within it firmly together.

# CHAPTER VII

## QUANTITY OF HEAT. MELTING AND SOLUTION

**113.** The melting of ice and the evaporation (drying up) of water are familiar instances of further effects produced by heating — **changes of physical state** — that we are about to take up and examine. But in order to study those phenomena effectively, we shall find ourselves obliged to pay attention to the quantities of heat that are transferred in such processes. Therefore it becomes necessary to develop the preliminary idea that heat is a measurable quantity (see § 84), and put it into more definite form.

First, it is reasonable to connect a greater or less quantity of heat with a particular weight or volume of water, for instance, as its temperature is raised or lowered, because one consequence of supplying heat to substances is a rise in temperature. And, similarly, higher temperature means more heat in any given portion of iron, mercury, or other material. Secondly, the total quantity of heat in a body must be made up of the heat distributed through all its parts. If any one temperature is common to every gram-weight of a leaden block, the total heat is equal to the quantity in the unit weight (1 gr.-wt.), taken as many times as there are grams-weight in the block. The same idea holds true for any other body that is *homogeneous* as regards *material* and *temperature;* and it could be applied equally well to volume, although quantity of heat is gen-

erally expressed with reference to weight of substance, rather than bulk.

The foundation of an acceptable plan for measuring heat is laid by putting these thoughts together. They lead us to recognize two important factors in the quantity of heat added to a body, or lost by it, during a transfer: (1) the weight of the body; (2) the rise or fall in temperature. Such a plan is used practically, in which heat-quantity is measured as proportional (not always *equal*) to

[Weight of substance heated or cooled] × [Change of temperature produced].

But it must be qualified by several considerations, before we are ready to use it freely.

**114.** To begin with, we know that unmistakable transfer of heat is not accompanied by change of temperature under all conditions. Ice must be heated somehow in order that it may be converted into water; but in locating the fixed points of thermometers (see § 92), the water, when first formed, is at the same temperature as the ice. Similarly, steam disengaged from boiling water is not hotter than the water, and yet heat must be supplied to the latter, if the process is to be kept going. These are typical instances, where change of physical state results from heating; and they make it clear that the proposed scheme of measurement cannot be brought to bear directly in those circumstances. The way is open, however, even there, to use it indirectly; and this will be made apparent when we come to discuss that group of phenomena. Secondly, we must not overlook the fact that the temperature will be stationary where no change of state occurs, for an object whose gain and loss of heat are balanced. Illus-

trate this with several examples. In such cases, we may require to know what (equal) quantities of heat are thus taken in and given out. Thirdly, the statements of § 113 include only different weights and temperatures for the same material. We need to look into the effect upon heat-quantity of substituting one substance for another of equal weight (Ex. 73).

Finally, observe that our estimates will be limited to quantity of heat added or subtracted; that is, to *differences* in the heat associated with a particular portion of some solid, liquid, or gas. The question concerning heat is always one of more or less, and not of presence or outright absence (see § 95). Just because the Centigrade scale indicates merely differences of condition from zero Centigrade, the temperature-factor in quantity of heat introduces only a corresponding comparison of some other state with the state of the same body at zero, in answer to the inquiry, "How much heat has been gained (body above zero) or lost (body below zero)?"

## THE CALORIE AS A HEAT UNIT

**115.** Supposing that two portions of water at different temperatures are mixed (without loss or gain of heat otherwise), each carries its own quantity of heat into the mixture, leaving the total quantity unchanged. Transfer of heat will go on *within the mixture*, between the hotter and the colder water, until they reach a common temperature; the same quantity being lost by the former and gained by the latter, because the total is only redistributed by mixing. The results of actual trial (Ex. 73, (1), (2)) are influenced to some extent by unavoidable leakages of

heat into the water, or out of it, during the operation. But, on making due allowance for such leakage, the common temperature approaches: —

(1) The arithmetical mean (*i.e.* the half sum) of the temperatures just before mixing, when the portions are equal in weight. Since this mean of two numbers lies half-way between them, the common temperature on that supposition is equidistant from the original temperatures; the movement toward the former is equal from both extremes. We can conclude that a fall of one degree in the hotter water raises the temperature (sensibly) by one degree in the colder water of equal weight.

(2) The average, taking account of weight and temperature, when unequal weights are mixed. Let the weights of water be $W_1$ and $W_2$, their original temperature $T_1$ and $T_2$, and their common temperature $\bar{T}$. Then, according to the fundamental idea of average (see § 43),

$$(W_1 + W_2)\bar{T} = W_1 T_1 + W_2 T_2. \tag{14}$$

The preceding condition (equal weights) falls under Equation (14) as a special case. For, if the weights are equal, $W_1 = W_2$, and

$$\bar{T} = \tfrac{1}{2}(T_1 + T_2). \tag{15}$$

Statements (1) and (2) above are not restricted to water; they hold good in general, when two portions of the *same* solid or liquid material at different temperatures are mixed.

**116.** When unequal (or equal) weights of *different* substances are brought together, the rule given by Equation (14) fails to apply (Ex. 73, (3)). No such simple relation is recognizable, either, by the device of measuring

volumes used, instead of the weights. The common temperature obtained on mixing water with water is modified considerably on replacing one portion of water by mercury, or lead, or copper, or glass, at the same original temperature, — either gram-weight for gram-weight or bulk for bulk. The same sort of individual behavior that marks the expansion of various materials is shown here. The heat given off by 1 gr.-wt. of water, when it cools through 1°, will raise about 11 gr.-wt. of copper, or 30 gr.-wt. of mercury, through that interval of temperature. The plan for measuring quantity of heat that was outlined at the end of § 113 does not become definite, therefore, until we name (3) the material heated or cooled, in addition to (1) its weight, and (2) the temperature interval.

This last thought gives the key to the situation in fixing completely the measure of heat-quantity. Water is selected as the standard substance (see § 26), and it is agreed: —

(1) That any transfer of heat in which other substances are involved shall be reduced to an *equivalent* process of heating and cooling water.

The numbers instanced above for copper and mercury suggest how that reduction can be made; let us work out an illustration. Suppose that 500 gr.-wt. of copper are heated to 100°, then plunged into 900 gr.-wt. of mercury at 15°, and stirred around until a common temperature is reached. Since 11 gr.-wt. of copper are equivalent to 1 gr.-wt. of water (for the same temperature interval) in relations of heat-transfer, 500 gr.-wt. of copper are the equivalent of $500 \times \frac{1}{11} = 45.6$ gr.-wt. of water. Similarly, 900 gr.-wt. of mercury replace $900 \times \frac{1}{30} = 30$ gr.-wt. of water. If 45.6 gr.-wt. of water at 100° were mixed with

30 gr.-wt. of water at 15°, we should find as the common temperature, employing Equation (14), § 115,

$$\bar{T} = \frac{45.6 \times 100 + 30 \times 15}{45.6 + 30} = 66°.3. \qquad (16)$$

And this would be the common temperature attained by the mercury and copper, provided that incidental losses of heat were neglected, compensated, or allowed for.

(2) That quantity of heat shall be expressed numerically in terms of a **unit of heat**, equal to the amount gained or lost when a change of 1° (Cent.) occurs in 1 gr.-wt. of water. The unit for quantity of heat thus specified is called the **calorie**. Then measuring in calories, the quantity of heat ($H$) transferred in any process to which these ideas apply (see § 114) can be calculated: —

$$H = [\text{Weight of water heated or cooled}] \times [\text{Change of temperature produced}]. \qquad (17)$$

The weight of water will be "equivalent," as explained under (1) above, where the substances actually employed are not water. Thus, in the preceding numerical example, the copper loses 45.6(100° − 66°.3) = 1537 calories.

Show that the mercury gains an equal number of calories.

Compare Equation (17) with the statement at the end of § 113. When will the latter become an equality, and when will it contain a proportional factor?

## SPECIFIC HEAT

**117.** Factors such as $\frac{1}{11}$ (for copper) and $\frac{1}{30}$ (for mercury), used in reducing other substances to their "water-

equivalents," are open to an interpretation differing slightly from that first given them. Each number of this kind can be regarded as a ratio in which two magnitudes are compared: —

(1) The heat-quantity (calories) required to produce a given change of temperature in a given weight of any material.

(2) The heat-quantity (calories) required to produce the same change of temperature in an equal weight of the standard substance (water).

By way of illustrative example, make comparison between 11 gr.-wt. of copper and of water, the change in temperature being 1°. Write the heat-quantity required for the water $H_W$, and that for the copper $H_C$. Then $H_W = 11$ calories; $H_C = 1$ calorie; and, consequently, $\frac{H_C}{H_W} = \frac{1}{11}$. Again, take 1 gr.-wt. of each substance, and 5° as the temperature interval. Here $H_W = 5$ calories; $H_C = \frac{5}{11}$ calories; but $\frac{H_C}{H_W} = \frac{1}{11}$ as before; the ratio evidently retains the same value for any equal weights of copper and of water, and equal changes of temperature. In like manner, if $H_M$ is the heat-quantity for mercury, compared with water on the same basis, $\frac{H_M}{H_W} = \frac{1}{30}$.

Such a ratio is known as the **specific heat** of the material in question, referred to water as a standard. Note that the word "specific," in this connection also, applies where comparison is made of the same quality in two substances (see § 26).

Show that $\frac{11}{30}$ would represent the specific heat of mercury referred to copper.

SPECIFIC HEATS: SOLIDS AND LIQUIDS

| | | | |
|---|---|---|---|
| Iron } Steel } | 0.11 | Silver | 0.06 |
| Glass | 0.19 | Mercury | 0.033 |
| | | Alcohol (15° to 40°) | 0.61 |
| Zinc } Brass } Copper } | 0.09 | Ether (15°) | 0.54 |
| | | Water | 1.00 |
| Lead | 0.03 | Ice (–° to 0°) | 0.50 |
| Kerosene | | Aluminum | |

**118.** Specific heats are not accurately the same at all temperatures, but the values in the table are to be understood as averages (see § 98, § 102); the range of temperature being 0° to 100°, except for ether, alcohol, and (of course) ice. The numbers given indicate to what extent specific heats of substances differ, but are not quoted as precise results; in fact, commercial materials are likely to show variations in such properties as these. It is worth noting that, if equal weights of water at 0° and at 100° are mixed, the common temperature (after allowing for losses) is found to be somewhat *above* 50°. This means, it is clear, that the average specific heat of water between 50° and 100° is greater than one, when referred to water between 0° and 50° as a standard; the ratio is about 1.01. We shall think of the standard for specific heats as determined by the *average* behavior of water for the interval 0° to 100°. Then the calorie may be specified as one-hundredth of the heat given off by 1 gr.-wt. of water in falling from 100° to 0°. The specific heat of water at any temperature is practically one, for our purposes; but the facts illustrate § 23.

Make the necessary measurements, calculate the specific heats of kerosene and aluminum, and enter them in the table (Ex. 74).

In what respect is water remarkable, as compared with other substances mentioned in the table?

How many calories of heat would be needed to raise $W$ gr.-wt. of substance, whose specific heat is $S$, from $T°$ to $T_1°$? Introduce the factors representing specific heats into Equation (14), § 115, so that it may apply to transfer of heat (without loss or gain on the whole) between any two substances. Which terms in the equation represent quantities of heat corresponding to differences between the state at any temperature and the state of the same materials at zero (see § 114, end)?

## HEAT OF FUSION: MELTING–POINT

**119.** When a vessel containing water and pieces of ice is heated, the temperature remains stationary at 0°, so long as any ice is present, provided that full opportunity for the contents to reach this common temperature is given by stirring (Ex.). The *time* required to melt a given weight of ice is influenced by supplying heat more or less vigorously, but the temperature during the process is constant. Since the quantity of heat added shows its effect in melting the ice, it is of interest to discover how many calories are required to convert **1 gr.-wt. of ice at 0°** into water of the same temperature. This is called the **heat of fusion** for ice; it is also spoken of as the **latent**[1] **heat** of water, perhaps with the idea that the heat is hidden from the thermometer.

[1] Consult the dictionary for this etymology.

Hot water of known weight and temperature forms a source of heat from which the supply can be measured readily. If its weight is $W$, it supplies $W\ (T_1^\circ - T^\circ)$ calories, in falling from $T_1^\circ$ to $T^\circ$. By melting ice under conditions that can be controlled in this way, its heat of fusion is found to be 79.5 calories (Ex. 75).

How many calories of heat must be supplied to 1 kg.-wt. of ice at 0° Fahrenheit in order to convert it into water at "blood heat"?

**120.** The melting process that we have been considering is reversed when water is frozen. If we begin at 10°, for instance, heat must be taken away until the water is cooled to 0°. At this "freezing-point," the temperature continues stationary while the water is being converted into ice, and nearly 80 calories of heat must be removed from each gram-weight of water as it passes into the solid state.

With many other substances, too, a definite constant temperature has been located as characteristic of the transition between the solid and the liquid form; whether it is viewed as melting-point or freezing-point depends upon the direction of the change. And in each case a measurable heat of fusion is recognized; but this is, for every substance thus far tried, less than the quantity of heat required in melting 1 gr.-wt. of ice, and varies from about 3 calories for each gram-weight (mercury) up to 65 calories (Chili saltpeter). Water is remarkable in this respect, as well as in its comparatively large specific heat.

A few melting-points have been selected for the accompanying table, mainly to illustrate what wide limits of temperature (heat-intensity) are called for in the manufacturing arts, especially in working metals. For the measurement of the higher temperatures in the table, we

rely upon the gas thermometer (see § 109); the mercury-in-glass thermometer must be abandoned at about the melting-point of lead.

MELTING (AND FREEZING) POINTS

| | | | |
|---|---|---|---|
| Mercury | −39° | Silver | 962° |
| Paraffine | 45°–50° | Gold | 1064° |
| Wax | 60°–70° | Copper | 1084° |
| Sulphur | 112°–120° | Glass | 1000°–1400° |
| Cane sugar | 170° | Cast iron | 1100°–1200° |
| Soft solder | 225° | Steel | 1300°–1400° |
| Tin | 231° | Wrought iron | 1500°–1600° |
| Lead | 327° | Platinum | 1775° |
| Aluminum | 657° | Iridium | 1950° |

Usually the passage from the solid to the liquid state may be called sudden; the "preparation" for melting occupies only a narrow range of temperature. But, in a few cases, signs of the approaching change appear far below the melting-point. Wrought iron and some kinds of glass are notable on this score; they soften at a red heat (500°–600°) to such an extent that they can be welded.

CHANGE OF VOLUME IN MELTING

**121.** These changes of physical state are marked by appreciable changes of volume, some instances of which should be mentioned here, on account of their practical bearing. Ice floats — as icebergs or in smaller pieces — because it is specifically lighter than water; the ratio is about $\frac{9}{10}$. The expansion of water in freezing is attended with some disadvantages when pipes and vessels are broken

by it; but the process is one of decided utility on a large scale. Rocks or clods are split apart, and the reduction of them to fine soil is furthered, by the repeated freezing of water in their small crevices. Water penetrates to the interior of rocks by "capillary action" at the exposed surfaces everywhere, as well as by trickling downward under the influence of weight.

Additional instances of expansion in the act of solidifying are furnished by cast iron, type metal, and bismuth. By virtue of this property, in connection with other advantages, the first two give good castings, because they are forced against the walls of the mould under pressure at the moment when they "set." One feature common to ice, cast iron, type metal, and bismuth is that they are crystalline in structure.

The examples spoken of above may perhaps be regarded as exceptions to the more general rule that solids expand in melting. When lead or wax has been melted, and solidifies in an open vessel, the free surface is likely to be concave to a greater degree than can be accounted for by contraction of the *solid* in cooling down from the freezing-point.

### EFFECT OF PRESSURE UPON MELTING-POINT

**122.** The melting-point of a substance is not precisely the same temperature always, but depends upon the condition of pressure under which the body is held. The melting-point is affected so very slightly, however, that we might rate it as constant, and pass its variation unnoticed, if a particular consequence of such a change were not made prominent in our experience. The instance alluded to is the alteration in the freezing-point of water

from its value 0° when the barometer height is 76 cm. It has been verified experimentally that the change is a lowering by 0°.007 for each added atmosphere of pressure (Ref. 19). Consequently, water placed under pressure exceeding that of the atmosphere remains liquid at temperatures just below 0°, though it will freeze if the excess of pressure is removed. And, if weight is supported by ice at 0° in the open air, a film of water may be produced at the bearing-surface (Ex. 76). In this arrangement, the liquid state (at 0°) corresponds to the increased pressure immediately under the wire; and, a thin layer of water being formed, the wire is pulled down through it. The water is forced up, released from the pressure exerted by the loaded wire, and frozen again. By repetition of these actions, the wire cuts its way down, and the seam closes completely behind it.

Do not forget to ask yourself where the heat of fusion comes from, when the water melts under the pressure of the wire.

This phenomenon is spoken of as the "regelation" of ice. It plays an important part in the "flow" of glaciers; also in the moulding of ice-fragments (or snow) into clear homogeneous blocks by pressure.

In order to avoid misunderstanding, it should be said that the melting-point of other substances is more usually (though not always) *raised* by increasing the pressure upon them; the changes are minute in every case.

## HEAT OF SOLUTION

**123.** Solids are reduced to the liquid condition of their solvents by solution; dissolving and melting are so fully

recognized as two methods of producing the same change of state, that the word "melt" is popularly applied to both of them. Salt is said to melt in water, or sugar in tea. These processes are not only equivalent in their results, but also similar in one vital feature: the heat of fusion required for melting has its parallel when solids are dissolved. In order to "liquefy" solids by solution, considerable transfers of heat to them may be necessary; this is called **heat of solution**, when reckoned for **1 gr.-wt. of substance** dissolved.

Evidence for this statement is found in the decided cooling which often accompanies solution, and brings the temperature during the process below that of the surroundings, and of both ingredients (Ex. 77). In such circumstances, we may draw the conclusion that either available method of converting the solid into liquid form involves the disappearance of heat; a certain quantity of heat becomes "latent." But, whereas the melting can occur at one temperature only, solution can go on within a wide range of temperature. In the former case, the quantity of heat transferred must be sufficient to maintain the substance at the melting-point; in the latter, the temperature will rise, fall, or remain stationary, according as the quantity of heat supplied is greater or less than that corresponding to the heat of solution, or is equal to it. Ammonium nitrate, the material suggested for Experiment 77, requires 65 to 70 calories for each gram-weight dissolved.

The condition that heat of solution is to be furnished somehow is turned to advantage in freezing-mixtures. When their temperatures fall in consequence of changes going on within them, the objects in contact with them

become sources of heat, and the heat-transfer is active in proportion to the difference of temperature established. Anything surrounded by the freezing-mixture is cooled in the effort to restore equality of temperature, and may be frozen under favorable circumstances. The mixture in everyday use consists of coarse salt and ice. In this case heat of fusion (for ice) and heat of solution (for salt) are both supplied by the ice-cream, wine, etc., that are cooled.

**124.** We still understand the word "dissolve" in its physical — not its chemical — application (see § 66 ; § 70, end). Within this meaning of solution, the number of instances is limited, where the choice is open to liquefy a solid either by melting or by dissolving it. Metals are insoluble, but they can be melted ; sugar, and many other chemical combinations, are easily broken up by raising their temperature, but they can be dissolved. In practice, therefore, the two processes supplement each other.

By referring to § 66, we have recalled the fact that rise of temperature is observed sometimes in connection with solution ; heat appears, instead of disappearing. Such examples of opposite result can be disposed of, however, without contradicting the idea that a solid is cooled by dissolving it, unless heat is supplied from some external source. We may follow up the suggestion that they represent weaker forms of *combination*, in addition to solution, which overcome and mask the cooling properly due to dissolving the solid.

Heat of fusion and heat of solution mark the demand for active measures, in order to bring a solid substance into the liquid state. But there are some signs of stability about the latter condition, when once it has been produced. If water is pure, and is guarded against jarring,

it can be cooled below 0° without freezing, even as far as − 13° (Ex. 78). And this phenomenon has its counterpart in solutions. For given materials, the saturation-point (see § 70) varies with the temperature; most substances (not all) dissolve more freely in hot water, for example, than in cold (Ex.). Usually, then, a solution that is saturated at a higher temperature will deposit solid on cooling; but the deposit from pure solutions in clean vessels free from disturbance may often be prevented (Ex. 79). The solution is then "supersaturated"; and (liquid) water below zero is "overcooled."

## CHAPTER VIII

### EVAPORATION. VAPOR-PRESSURE

**125.** Evaporation is an inclusive term for the change of liquids into the gaseous state, at whatever temperature that may occur; it is not restricted to the special conditions of boiling. The word suggests vapor; and we shall be speaking repeatedly of the water-vapor, alcohol-vapor, etc., formed by evaporation. But we must appreciate that water-vapor or steam, in this sense, is a clear, transparent, and colorless gas, not the white opaque cloud of partially condensed fog to which the name steam is given familiarly. And so with ether-vapor and the rest; they are like other gases in all essentials except the one noted in § 63. It is a common experience of our lives that the passage of water into this invisible gaseous form takes place at all ordinary temperatures. The soil loses its moisture in the sunshine; perspiration dries up on the skin; water disappears quickly from our pavements after a rain; the loss by evaporation from open reservoirs is an element that enters into calculations of water supply. The knowledge of similar facts about ether, alcohol, turpentine, and chloroform — more "volatile" liquids — is also widespread. But measurable traces of evaporation can be shown where we should be inclined to overlook them without delicate tests. Mercury, for example, is continually passing off as vapor at room-temperatures (Ex. 80).

## HEAT OF VAPORIZATION

**126.** Another item of general information to which we can appeal is that liquids cool surfaces from which they evaporate. Name several instances illustrating this fact. But while evaporation alone would "carry off heat," and tend to reduce temperature, heat may be supplied at the same time from some source, in quantity sufficient to keep temperature stationary or even raise it (see § 123). If water in a large open kettle is heated over a slow fire and reaches a maximum temperature of perhaps 60°, the loss of heat by evaporation is likely to be a prominent factor in locating this point of balance between loss and gain.

The heat which is thus employed to convert a liquid into vapor at the same temperature, — that is, to produce change of state only, — differs for equal weights of various liquids, and varies for the same substance at different temperatures. The quantity of heat corresponding to the evaporation of **1 gr.-wt.** is called the **heat of vaporization.** Like heat of fusion, it is regarded as latent heat; and for the same reason (Ref. 20). The heat of vaporization is returned when the reverse change of state is produced, and this suggests a simple plan for measuring it, by means of the number of calories given off by a known weight of the vapor in *condensing*. The most important case is that of water, for which the heat of vaporization at 10° is very nearly 600 calories (for 1 gr.-wt.); but it diminishes by about 7 calories for each added 10° up to 120° (Ex. 81). The plain meaning of this decrease is, that water is more nearly prepared to become water-vapor as the temperature is raised. The heat of vaporization is less, because the gap to be bridged by it is narrower. By way of rough

comparison, note that the heat of vaporization for alcohol is about 200 calories, and that for ether about 90 calories. It is another remarkable property of water that (weight for weight) it surpasses all other known substances in the quantity of heat transferred at the change between liquid and gas.

**127.** The accumulation in water of extreme values for specific heat, heat of fusion, and heat of vaporization makes it respond slowly to abrupt or excessive changes of temperature around it. These qualities combined cause it to represent a large available quantity of heat in small bulk, and adapt it admirably to be a carrier of heat on a small scale, as in systems of heating with hot water or steam. On the larger scale in nature, water serves as the reservoir for the sun's heat, in which the excess that reaches us in one day or season can be stored to remedy the defect at another time. Where large bodies of water like lakes or the ocean are present, they act as strong influences in cutting down the quicker fluctuations of temperature between day and night, or those of longer period between winter and summer; in this sense they are regulators of climate (Ref. 21).

Two peculiar properties that have been mentioned previously modify the consequences when the temperature of water is actually lowered to the freezing-point; they must be associated with the group named above in any adequate view of the functions exercised by water in shaping the facts of meteorology. The decrease of specific weight in both directions from 4° leads to the formation of ice near the free surface, and the expansion of water in freezing causes the ice to remain as a protecting cover to the water beneath.

Why should the air be warmed when snow or rain is "precipitated" in large quantities?

Can you assign any good reason for the practice of placing pails full of water in a greenhouse, in order to shield the plants against frost?

Do any of the properties of water that we have been considering contribute to its effectiveness in quenching fire?

Explain the fact that an unglazed (porous) jar can act as a water-cooler, and keep its contents below atmospheric temperature.

How are the ideas of § 126 illustrated by the use of ether-spray in surgery? Are they in harmony with the temperature conditions observed when ammonia gas is dissolving in water?

Would you expect "soda-water" from a "siphon" to be cooled by effervescing? Compare your expectation with the fact.

## VAPOR–PRESSURE: ITS MAXIMUM VALUE

**128.** In the open air, or any space like a room that is not tightly closed, evaporation may continue indefinitely, unless the supply of liquid is exhausted. The vapor of water and other volatile liquids that are exposed in uncovered vessels will then be carried among the constituents of the atmosphere by diffusion, aided by perceptible currents that cause circulation, and tend toward homogeneous mixture (see § 67, end). But when the enclosure above the free surface is limited and gas-tight, the process of evaporation comes to a standstill at a condition of balance, which it is our next purpose to examine.

Allowing ether or alcohol to evaporate into a vacuum, while the temperature is controlled by a water-bath, and the quantities are such that some of the material is left as liquid, it is observed at each (constant) temperature that the pressure exerted by the vapor soon reaches its greatest value, and then remains stationary (Ex. 82). At any particular temperature, if the volume of the enclosure be made less or greater, the vapor and the liquid adjust themselves to the new relations by condensing or evaporating until the pressure corresponding to that temperature is restored (see Ex. 34). The greatest value of the pressure which any vapor (in the presence of its liquid) can exert at a given temperature, we shall distinguish as the **maximum vapor-pressure** for that substance and temperature. We find the maximum vapor-pressure of liquids increasing as the temperature is raised.

**129.** If the enclosed space is originally occupied by air under any pressure, the time required in attaining the stationary condition is increased, but the ether or alcohol evaporates finally to the same extent as though a vacuum had been offered to its vapor. The maximum vapor-pressure corresponding to the prevailing temperature is merely added to that exerted by the air (Ex. 83). The added gas (ether-vapor; alcohol-vapor) is independent of the previous occupants, here as in other cases (see § 64; § 68). And this statement holds true, so long as the vapor and the (original) gas are really indifferent to each other. Chemical combination in its stronger or weaker forms, however, introduces deviations from this rule.

The final pressure due to both gas and vapor depends in part, of course, upon whether the enclosed volume is maintained practically constant (as in Experiment 83), or

is allowed to change. In the former case, if $P_A$ is the original gas-pressure, $P_V$ the maximum vapor-pressure for the (constant) temperature $T^\circ$, and $P$ the final pressure in the enclosed space,

$$P = P_A + P_V. \qquad (18)$$

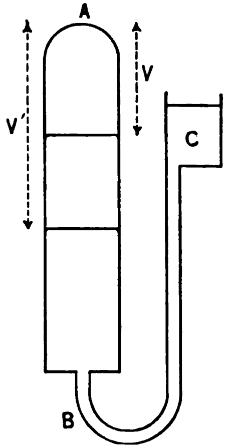


FIG. 45.

Let us follow out the case where the volume is altered from $V$ to $V'$ (Fig. 45) by lowering the jar $C$ which contains mercury, and thus adjusting the level in $AB$. The *gas* is supposed to follow Boyle's Law; hence its part ($P'$) of the final pressure is $\frac{V}{V'}P_A$ (Eq. 6, § 63). The maximum vapor-pressure in contact with the liquid at $T^\circ$ is the same for $V$ and $V'$. Consequently,

$$P = \frac{V}{V'}P_A + P_V. \qquad (19)$$

BOILING–POINT

**130.** When a few liters of tap water are heated in an open kettle over a fire or a powerful gas-flame, the temperature is raised quickly at first, but becomes practically stationary so soon as the water begins to boil, and is not carried higher by making the fire hotter, or lighting a second gas-burner, though the former change adds to the intensity of the source, and the latter to the quantity of heat available. The effect of these devices is only to "boil the water away" faster; that is, to increase the rate of evaporation. The greatest temperature attainable in such

circumstances is called the boiling-point for those conditions; at the sea-level it is about 100°. The escaping steam differs but slightly in temperature from the boiling water; and we have learned to rely upon the unchanging character of these results in fixing the steam-point on our thermometers (see § 92). Alcohol, or mercury, or other liquids can be used to replace water without changing the phenomena essentially, except that the stationary temperature at which the substance boils may lie above or below 100°. In terms of these observed facts, the **boiling-point** of a liquid is described as the **highest temperature** to which that liquid can be raised in an open vessel, the supply of heat being unlimited in quantity and intensity. The heat transferred is (mainly) disposed of by evaporation; a greater transfer by more rapid evaporation.

It should be added, however, that certain experimental precautions are needed, if the real temperature of steady boiling is to be indicated in this way. Pure liquid can often be heated several degrees beyond that point, especially in smooth clean vessels of glass (Ex. 84). Vapor is likely to be released periodically, with some violence, causing the temperature to sink to the normal value. But it rises again, and the cycle is repeated. This "bumping" can usually be got rid of by putting a few rough fragments of metal in the vessel. The possibility of "superheating" liquids suggests once more an effective stability in that physical state, which we have remarked elsewhere (see § 124, end).

**131.** As the bubbles of steam pass up through water that is boiling in an open vessel, they are visibly able to resist the pressure exerted upon them, which is that transmitted from the atmosphere, plus a small amount due to

the weight of water. This fact offers a clew in estimating the magnitude of the maximum vapor-pressure at the boiling-point; and direct experiment confirms the inference (Ex. 85). These measurements furnish us with a second statement descriptive of boiling. The boiling-point is the temperature at which the maximum vapor-pressure is equal to the pressure on the free surface of the liquid. While dissolved solids, as well as the irregularities noticed in § 130, affect the indications of a thermometer that is immersed in a boiling liquid, these causes are without influence upon the temperature of an escaping vapor whose pressure is in balance with the external pressure (Ex. 86). Hence the steam-point of a scale is to be marked in steam, rather than in boiling water.

The insight obtained here into the special conditions at the boiling-point enables us to see why that temperature should depend upon barometer height, and in general vary with external pressure of any origin, that is exerted upon the boiling liquid. Since maximum vapor-pressure and temperature increase together, the latter must be higher, in order that the former may be brought to equality with a greater pressure upon the free surface. The conclusion that water will boil above or below 100°, if the pressure is greater or less than one atmosphere, can be easily verified (Ex. 87). The displacement of the steam-point averages very nearly $\frac{3}{8}$ of one degree for each centimeter of barometer height within the range 68 cm. to 78 cm.

**132.** In extending thermometer-scales far beyond 100°, boiling-points of other liquids render good service, as that of water does in fixing the steam-point, because the temperature of a vapor at a given maximum vapor-pressure is always accurately the same. Such points having been

once definitely located with a gas thermometer, they can be used to calibrate other instruments. The list below includes a few instances of this kind, in addition to water.

BOILING-POINTS (Pressure = 1 atmosphere)

| | | | |
|---|---|---|---|
| Ether . . . . | | Naphthaline . | 218° |
| Alcohol . . . | | Mercury . . . | 357° |
| Water . . . | 100° | Sulphur . . . | 445° |
| Aniline . . . | 184° | Zinc . . . . | 930° |

Enter your own observed values for ether and alcohol, recording the corresponding barometer heights, if necessary.

The variation of boiling-point with external pressure upon the liquid has its effect within steam boilers, where the temperature of the steam will range from about 140° to 180°, for pressures of *the steam* lying between 4 and 10 atmospheres. What *gauge-readings* in pounds-weight to 1 □ in. are equivalent to these limits?

Accordingly, water and steam from a boiler are effective sources of heat, when circulating through steam coils or "steam jackets," in many industrial processes which could not be operated with water and steam at 100°. Materials are also "digested" in direct contact with steam and water at temperatures higher than 100°, in order to hasten solution, or extract certain ingredients. In sugar refineries, on the other hand, a boiling-point below 100° is maintained in the "vacuum-pans," because unprofitable changes in concentrated sugar-syrup are produced by heating it to the standard boiling-point of water. At elevations much above 2000 meters, the diminished atmospheric pressure

reduces the temperature obtainable with water boiling in open vessels to an extent that interferes with cooking. At 2000 meters, the average barometer height is 59 cm., and the corresponding boiling-point of water is 93°.

## HUMIDITY

**133.** Water-vapor is a recognized normal part of our atmosphere, and contributes its share regularly to the pressure indicated by the barometer (see § 64). That share varies with season, time of day, and locality, but it may be represented by as much as one or two centimeters of the barometer reading. Taking nitrogen, oxygen, and water-vapor as the constituents of the atmosphere (only small proportions of other gases are present), each exerts its own pressure independently, and the atmospheric pressure is a sum-total of the three. A barometer reading of 76 cm. is then composed of three parts, whose magnitudes are, in a typical case: —

| | |
|---|---|
| (1) Due to nitrogen . . . . . . . . . . | 59.25 cm. |
| (2) Due to oxygen . . . . . . . . . . | 15.75 cm. |
| (3) Due to water-vapor . . . . . . . . . | 1.00 cm. |
| Total (atmosphere as a whole) . . . | 76.00 cm. |

At any temperature that prevails locally, this pressure of water-vapor may range from its maximum downward almost to nothing, according to circumstances. During rainy weather, the condensation ("precipitation") that is occurring gives evidence that the maximum has been reached; in arid regions like some districts of Nevada, water-vapor may be at times nearly absent from the atmosphere.

Evaporation always tends toward establishing the largest value of vapor-pressure possible under the conditions; and, other things being equal, the *rate* of evaporation will be less as the maximum is approached, greater as we depart from it. Now it happens that evaporation and condensation of water-vapor affect our lives in various ways; these processes enter into the drying of fruit and of clothes, they touch our personal comfort through smaller matters like perspiration, and they operate in larger dimensions through the weather. So it frequently concerns us to know whether water will evaporate rapidly, or whether water-vapor is ready to condense, and to bring about the proper conditions for either process. And then the more important question is, not what pressure of water-vapor exists in a particular space, but, rather, how close is that pressure to its maximum value for the temperature there. Use definite numbers to illustrate this point. Compare two rooms whose temperatures are 3° and 25°, supposing the pressure of water-vapor in both to be represented by 0.57 cm. of mercury, which is the maximum pressure for 3°. In the colder room, no evaporation at all can take place, and a slight fall of temperature will cause condensation on the objects within it, its walls, and its windows. In the warmer room, evaporation will go on readily, because there is a wide margin between 0.57 cm. and 2.36 cm., corresponding to the maximum pressure for 25°.

**134.** These thoughts give its prominence to the idea of **humidity**, which we find expressed as part of the meteorological record or elsewhere, in the form of a fraction or its equivalent in percentage. Humidity is the ratio of the actual pressure of water-vapor in any space (out-of-doors or enclosed) to the maximum value that it could have at

the same temperature. Connecting this notion with the example just cited, the humidity in the warm room would be $\frac{0.57}{2.36} = 24.15\% = \frac{1}{4}$ (nearly). Evaporation is relatively brisk for small values of the humidity, slackens as it grows greater, and ceases entirely at the value 100% or 1. Put into other words, this means that evaporation proceeds more rapidly, the more decidedly conditions differ from those of *balance*, at the maximum vapor-pressure (see § 86, (2)).

Evaporation of perspiration from the skin is an active agency in keeping our bodies cool during hot weather, or under any circumstances of exceptionally high temperature, like furnace rooms; and the relief is furthered by elements that favor rapid evaporation. Days when great humidity is combined with "extreme heat" (*i.e.* high temperature) are likely to be registered by cases of sunstroke, the excessive distress being promoted by the feeble evaporation. Each gram-weight of water evaporated at 37° carries off about 575 calories of heat (see § 126). And 150 gr.-wt. of water (say half a glassful), converted into water-vapor at the skin, would cool by more than 1° a man who weighs 75 kg.-wt.; assuming the average specific heat of the human body to be that of the water which makes up about two-thirds of us.

**135.** When it is desired to keep up rapid evaporation, a second condition to be provided for is the effective removal of water-vapor; otherwise the process would be impeded by the increased humidity due to its own products, and cease when the maximum pressure was reached. Diffusion is often too slow for the purpose, and then the water-vapor is generally dispersed by currents of air, which mix with it and carry it off mechanically from contact

with the surfaces where the change of state occurs. It is the local humidity *there*, of course, that determines whether water will be converted into vapor, not conditions at a distance of twenty or thirty centimeters. A porous water-jar cools its contents more satisfactorily when a breeze is stirring, because the water-vapor is blown away from the jar as fast as it can form, and the humidity there is kept at smaller values. The refreshing influence of fanning or of "sitting in a draft" is to be credited to similar favorable conditions. These remarks apply, too, where complete or rapid drying is the result sought, rather than cooling. In that case, the object is to exhaust the supply of liquid; and that end will be attained sooner, the more quickly the water evaporates. Hence the drying rooms in laundries, paper-mills, fruit-driers, etc., are (1) heated; and (2) equipped with "blowers," or other means of maintaining vigorous circulation of air, whose currents shall be strong enough to clear away the water-vapor. This action is essentially like that of a swift stream in carrying off the earth of its banks.

Why are drying chambers heated? [See § 133, numerical example; and the first paragraph of § 134.]

The wet-bulb thermometer (Ex. 88) repeats the conditions of the water-cooler; and comparing it (on even terms in other respects) with the dry-bulb thermometer is one means of determining practically the local humidity. The data for the tables that are used had to be obtained first by direct measurement in other ways, of the humidity corresponding to a given difference of readings between the wet-bulb and the dry-bulb instrument.

When will the divergence of the readings be greatest? Can it vanish?

## DISTILLATION

**136.** If steam from boiling water is allowed to diffuse through a large space like a room, in which the temperature is constant and the humidity is at first small, the vapor-pressure will be reduced by expansion in occupying the larger volume. This is joint occupation with the air originally in the room, of course, and any increase in total pressure (see § 133), due to the added water-vapor, will be relieved by escape through small openings — flues, keyholes, etc.; the room is not supposed to be air-tight. So long as the reduction of vapor-pressure is sufficient to keep the water-vapor below its maximum for the temperature of the room, there need be no condensation. But condensation will begin when that maximum is reached in the space; it will begin sooner, other things equal, the smaller the volume of the space; and it will continue while the boiling goes on under those conditions. A similar general description of what happens will still apply, if the water evaporates at a constant temperature below its boiling-point, and if the liquid evaporated is not water.

In any such circumstances, where the vapor from a liquid that is maintained at a higher temperature escapes into a cooler space of constant *total* pressure and lower temperature, three simultaneous processes can be observed: —

(1) The liquid evaporates at its free surface (quietly or with boiling), in the effort to establish there the maximum vapor-pressure corresponding to the higher temperature.

(2) The vapor is carried by circulating currents and diffusion throughout the cooler space, with a consequent

tendency to raise the vapor-pressure above the maximum for the lower temperature.

(3) Condensation in the cooler space goes on continually, because a vapor-pressure greater than the maximum cannot exist at a given temperature.

The final result is that liquid is transferred from the place of higher temperature to that of lower, conveying with it the quantity of heat that is taken up where the liquid is vaporizing, and given off again where the vapor condenses. This heat must be disposed of somehow, if the lower temperature is to remain constant; it is supplied by the source of heat used to keep the liquid hot.

**137.** The operation called **distilling** realizes the main features of the case just discussed. A liquid is heated or boiled in the vessel *S*, called a still (Fig. 46), from some source of heat like a fire, or a steam-coil, or a gas-flame; the vapor escapes into a pipe or worm *W*, which is kept cool by immersing it in a tank *T* through which cold water flows; the vapor is condensed, and runs off at *A*. The total pressure inside the still is sensibly that of the atmosphere.

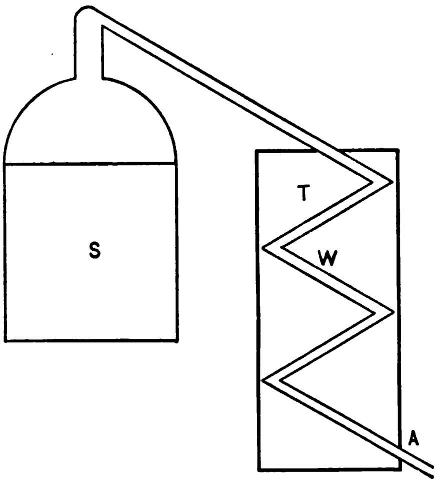

FIG. 46.

Distillation is employed when it is desired to separate a liquid from non-volatile dissolved substances. This is done, sometimes to "purify" the liquid, and sometimes in order to secure the residue. Distilled water, which is now used for so many purposes, has been thus purified; and mercury required in filling barometers or thermometers is often distilled as an effectual means of removing impurities. On the other hand, the amalgams of gold yielded by some metallurgical methods are "retorted"; that is, the amalgam is placed in a retort, and the mercury solvent is distilled off and condensed for repeated use, leaving the gold in the residue. Operations of drying, like those mentioned in § 135, differ from distillation only in the circumstance that no pains are taken to condense and regain the evaporated liquid.

Distillation can be carried on in a gas-tight enclosure, a permanent difference of temperature being maintained between its remote parts by local heating and cooling; the vapor-pressure is merely added to that exerted by air or other gas which is present. The diagram (Fig. 46) might be adapted to such a scheme if the worm were closed with a tap at *A*. Since boiling-point is lowered when the pressure at the free surface of the liquid is decreased, while diffusion of vapor takes place more rapidly in the absence of other gases, it is occasionally advantageous to distil a liquid from one part to another of a vessel that has been closed after producing a partial vacuum within it. Under these conditions, for instance, a *quiet* evaporation of mercury at about 200° is kept up, the cooling surface being at room-temperature. It is possible to use glass vessels, and the absence of spray from boiling favors the purity of the distilled product.

The so-called cryophorus emphasizes the thought that local differences of *vapor-pressure* are the vital condition of distillation (Ex. 89). Explain in detail the action observed. What does the word "cryophorus" imply? Do you accept that idea as correct?

The vapor-pressure may be lowered at one place by absorption, instead of cooling (Ex. 90). This is the principle of the "ice-machine" in one form (Ref. 22).

**138.** The pressure of water-vapor in an enclosed space does not disappear entirely on cooling to 0°, where water passes into the solid state. Its maximum value at $-10°$ is still 0.2 cm. of mercury. And this agrees with the observation during seasons of unbroken cold, that ice and snow evaporate visibly at temperatures below their melting-point. Camphor, sal ammoniac (ammonium chloride), and a few other substances are regularly convertible (under atmospheric pressure) from the solid state directly into vapors, and condensation then changes them from vapor into solid, the liquid state being omitted (Ex.). Such materials are said to sublime, and the modified form of distillation, when they are evaporated and condensed, is called **sublimation**; it may evidently serve as a means of separating impurities.

In a space above a mixture of alcohol and water, the vapors of both are present, but the vapor-pressure of the alcohol is greater, because its boiling-point is lower. The mixture boils at the temperature for which the total vapor-pressure (*i.e.* the sum of the two partial pressures) is equal to the external pressure; but, it may be remarked, that total at a given temperature is less than the result of adding the maximum vapor-pressures of the pure liquids for the same temperature (Ex.). The maximum vapor-

pressures of alcohol and of water at temperatures from 60° to 80° are shown below as centimeters of mercury: —

| | 60° | 65° | 70° | 75° | 80° |
|---|---|---|---|---|---|
| Alcohol . . . . | 35.0 | 43.7 | 54.1 | 66.5 | 81.3 |
| Water . . . . | 14.9 | 18.7 | 23.3 | 28.9 | 35.5 |

This is further evidence that the two liquids are not indifferent to each other; in fact, "absolute" alcohol is hygroscopic. Connect with the above result the action between alcohol and water in Experiment 5, and the influence of dissolved substance upon vapor-pressures in Experiment 86.

If dilute alcohol be distilled, then the distillate will be stronger (Ex.), and, within certain limits, the proportion of alcohol can be raised still farther by repeated distillation. Why cannot *pure* alcohol be obtained in this way? Does your experience suggest any device for removing the last traces of water?

This method of regaining alcohol from its mixtures with water is one stage in the manufacture of distilled liquors, and of strong alcohol for commercial purposes. Other mixtures of liquids having different boiling-points can be more or less completely separated into their constituents in a similar way; the plan is often spoken of as **fractional distillation.**

# CHAPTER IX

## SOURCES OF HEAT. CONVEYANCE OF HEAT

**139.** If we count up the sources of heat that are directly available for ordinary purposes of heating, we find them limited to sunshine or the burning of some fuel in the large majority of instances. Electrical heating is sometimes resorted to, but it is still restricted to a relatively small number of special contrivances. And heat derived from friction or other forms of mechanical action is on the whole incidental, apart from a few examples like "striking a match," and setting off percussion caps or torpedoes by a blow.

Collect evidence from your experience, that heat may be produced in each of these four ways.

Neglecting some minor items like hot springs and volcanoes, we name, then, four sources of heat: (1) sunshine; (2) fuel; (3) mechanical action; (4) electrical action. There are good reasons, as we shall see, for including all these headings in our list of sources, although the useful supply of heat comprised immediately under the last two is insignificant as compared with that falling under the others.

It is to be remarked about each type of source, in the first place, that the phenomena of heat do not appear alone, but accompany others that seem entirely different in character. Thus light, as well as heat, goes with sun-

shine. The burning of fuel has a chemical side, combustion being in reality a combination — mainly of the air's oxygen with hydrogen or some variety of carbon. Mechanical action involves forces, and setting bodies in motion or stopping them; and complicated special phenomena are bound up with the production of heat by electrical means.

## RELATIONS OF HEAT TO OTHER PHENOMENA

**140.** On looking into these matters attentively, we gather from them the suggestion that light, chemical processes, mechanical action, and electrical phenomena are *causes* of heating under certain conditions. And the impression that there are connections of cause and effect here is deepened, when we notice, secondly, that the relations are not one-sided; with altered conditions, light and other phenomena may appear as *consequences* of heating. Iron or charcoal is rendered glowing and luminous by the same forge fire that makes it hot; the carbons of an arc-lamp give out successively red, yellow, and white light, as their temperature is raised; various colors are seen in the flames of fireworks. Looking for chemical changes as results, we find that heating in a kiln converts limestone (calcium carbonate) into lime (calcium oxide); that iron is released from the compounds of its ores by the intense heat of the blast-furnace; and that heated sulphur or steel will burn in air, the latter fact being made evident by the sparks that are showered from a knife ground on an emery-wheel.

By pursuing this line of thought a little farther, the heat-supply of a particular place and time can be con-

nected with preceding processes as their sequel; and the mode of its conveyance to the spot where it is used is full of instruction as to transformations that occur by the way. The wood that we burn gathered its constituent parts and grew under the stimulus of past sunshine; coal (so the geologists tell us) is only wood that has been buried and changed. When the cold of winter is moderated with such fuel, through any devices of our modern houses, we are in a certain sense drawing upon the stored effects of sunshine to make good a present deficiency of it. If coal is burned under a boiler, some of the heat goes into the steam, which may produce motion in the parts of an engine and a dynamo. Using the wires of the circuit as guiding channels, the dynamo hands on to a distant arc-lamp the possibilities of sunshine stored in wood long since grown, to reappear once more as light and heat.

**141.** Enough has been said in this general way to offer strong reasons for studying more closely the history of a heat-supply, and marking the critical points at which it emerges into the form recognized as heat, after passing through stages where it is effectually disguised. As it happens, the changes back and forth between heat and mechanical effect are directly open to examination, and the measured equivalent in that form for a given number of calories is easiest to trace by simple means. We shall therefore turn first to consider that particular transformation.

However natural the idea can be made to appear now, that quantities of heat may come and go under other forms, it must not be overlooked that heat was at first undetected in these protean[1] changes. Until about 1800,

[1] Does the parallel between Proteus and Heat strike you as a just one?

the belief was general that any quantity of heat preserves its identity in the same sense that a given sample of mercury does. That is, it was thought to continue unaltered in nature and amount, while associated with the same body, or when transferred to another, just as the mercury remains mercury still and retains its weight, whether it occupies the same vessel, or is poured into any other. This earlier view about heat has been alluded to once before (see § 8), and is implied still in the surviving phrase "latent heat" (see §§ 119, 123, 126). But to what extent is latent heat properly *heat* at all? We shall find our answer to that question in what follows.

## HEAT AND WORK: THEIR CONNECTION

**142.** The experimental study of the relations when heat is developed by mechanical contrivances was undertaken systematically by Count Rumford, in connection with the boring of cannon (Ref. 23). He proved that a practically unlimited number of calories could be really *generated*, or brought into existence as heat, so long as the boring was kept up by horse power; and discovered how to express the equivalent for the heat added, in terms of the work done by the horse. Sir Humphry Davy confirmed the conclusion that heat is in fact "made out of work" on the spot. After excluding carefully all other sources of heat, he was able to melt pieces of ice by rubbing them together. As more heat, by a considerable number of calories, was represented in the water produced than in the original ice, the argument is strong that the work of rubbing decidedly increased the stock of heat.

The meaning here is conveyed by taking the word

"work" in a general sense that is well understood; but more definite ideas must be attached to it, if we are to measure work, put it on a level with quantity of heat, and examine into their equivalence. When the **work** done under any conditions is spoken of in Physics, we intend to take account of two elements combined: (1) the forces that are acting; (2) the distance through which the body that they act upon is moved. The importance of both force and distance can be felt, without going beyond such familiar illustrations as a walk or a wheel-ride. Other things being equal, the "wear and tear" of a journey increases with its length; that is, with the accumulation of distance through which the forces act, that are called into play in taking a step or driving the pedals. And, when comparing walks or rides of equal length, the effect of steeper climb (*i.e.* stronger force in lifting) is clearly apparent in greater tire. Nor are these personal impressions only; the same facts are registered in a locomotive-tender by the greater consumption of coal on a longer run, or in order to surmount a steep grade. In ascertaining the work contributed by any force, therefore, we need to know both the magnitude of that force and the actual displacement of the point at which it acts. But it is agreed that the displacement shall be reckoned always along the line of the force; for example, it is *vertical* distance alone that counts, where the work connected with weight is to be considered.

## MEASUREMENT OF WORK

**143.** We shall measure work by multiplying together force (expressed as grams-weight) and distance moved

along its line (measured in centimeters). Let $F$ and $D$ stand for these factors; then

$$\text{Work} = F \times D. \tag{20}$$

The number obtained for the work is one, or a unit of work is done, when a force of 1 gr.-wt. acts, while a displacement of 1 cm. occurs in the line of the force. As a full statement of that particular case,

$$\text{Work} = 1 \times 1 = 1 \text{ [1 gr.-wt. acting through 1 cm.]}. \tag{21}$$

The phrase within brackets is useful in showing our plan of measurement; it is adopted as a descriptive name of the work unit, but shortened into **gram-centimeter**, and written "gr.-cm," for convenience in daily application. All these ideas are implied in the compact saying, "Work is measured in gram-centimeters"; that is, by comparison with 1 gr.-cm. as a standard.

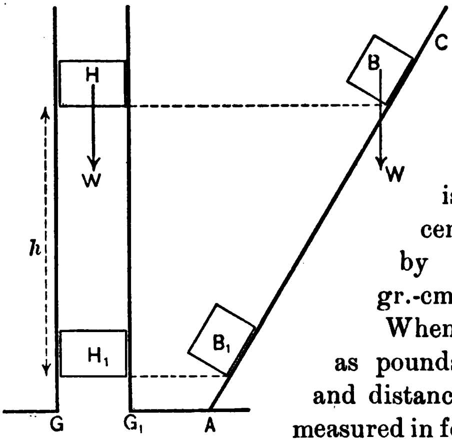


FIG. 47.

When forces are expressed as pounds-weight (see § 22), and distances as feet, "Work is measured in foot-pounds" (written ft.-lbs.). Expand the quoted phrase according to the preceding model. How many gram-centimeters of work are equal to 1 ft.-lb.?

A numerical example furnishes the best illustration for some of the points noted. The hammer, $H$ (Fig. 47), of a

pile-driver weighs 250 kg.-wt., and falls 6 meters to $H_1$, between vertical guides, $G$, and $G_1$. From these data, the work of the weight is calculated to be

$$(250 \times 1000) \times (6 \times 100) = 15 \times 10^7 \text{ gr.-cm.}$$

If a block $B$ of the same weight slides along an inclined plane $CA$, from $B$ to $B_1$, the vertical displacement or difference of level being 6 meters also, the factors representing force and distance are unchanged, and the work of the weight in these circumstances is again $15 \times 10^7$ gr.-cm. The same amount of work would be done, of course, if half the weight acted through twice the distance; or in general, if the weight were changed in any ratio, and the distance in the inverse ratio, the product, therefore, remaining constant.

## POSITIVE AND NEGATIVE WORK

**144.** Since the weight pulls back while the hammer is being hoisted, the elements of vertical force and displacement are both present, and it would appear that weight is doing work during the lift as well as during the fall, the quantities of work being evidently equal in magnitude when the hammer is returned to the original position $H$. But whereas weight causes the motion downward, and quickens the speed in that direction, the hoisting of the hammer is hindered by its weight, whose influence is to make the motion slower. We recognize these opposed relations to the actual displacement or motion by calling the work of the weight positive from $H$ to $H_1$, and negative from $H_1$ to $H$. In the present case, the work of the weight will be zero, on the whole, when the hammer regains the position from which it started.

Following out the same idea, work is to be marked with a plus sign, if the corresponding force favors the motion that actually occurs; and the work of a force that resists or hinders is marked with a minus sign. For example, the rubbing of *H* (Fig. 47) against the guides, or of *B* against the plane, would result in negative work, because such frictions always act in opposition to the motion, either upward or downward. Where several forces are in operation, each may do work (positive or negative) for itself; the total work is then an algebraic sum. The sum will be positive if terms with a plus sign, taken together, exceed the others; the sum will be negative in the reverse case. When weight acts alone, and does positive work as a body falls, it quickens the speed; and we can regard it as a practical test of the sign to be attached to any sum representing total work, when several forces coöperate, to observe whether the speed of the body acted upon becomes greater or less.

If increasing speed means positive work on the whole, and decreasing speed negative work, how do you interpret constant speed?

A train is being pulled up a grade steadily at 48 kilometers an hour. What sources of positive and negative work do you detect? If these conditions continue for one kilometer, how much work is done in that interval?

**145.** In algebra, the product of two factors is positive when they have the same sign, and negative when they have contrary signs. Looking at Equation (20) (§ 143) algebraically, it is plain that $(+F) \times (+D)$ and $(-F) \times (-D)$ both give the plus sign for the corresponding work. But this is no more than another way of indicating the requirement that the body must go the same way that the force

pulls (or pushes), in order that the work may be reckoned positive. For *F* and *D* are in the same line (see § 142, end), and the only contrast between (+) and (−) is then that quantities point in opposite directions if they have contrary signs (see § 25). One sign must mean one direction.

These ideas about work are the foundation for considering the measurable relation between heat and mechanical effect, which is the special end in view just now (see § 141). In the example selected to illustrate them (Fig. 47, § 143), the aim is to avoid superfluous difficulties, and present a simple form of the main thought. The conditions there are purposely simplified in two respects, which it may be well to notice in preparation for a somewhat broader statement to be made in the next chapter. First, the calculation of work is made easier by choosing weight to do it — a force that remains constant in direction and magnitude. The constancy of direction enables us to measure the proper total distance along a (vertical) straight line. The alternative state of affairs is shown in the diagram (Fig. 48), where the ball *B* is threaded on a curved wire *AEC*, and pulled along it by a string *S*, lying close to the wire.

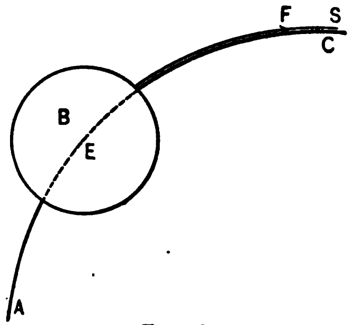


FIG. 48.

How should the distance *D* be measured here?

The constancy of magnitude in weight is the ground for multiplying the total distance by the same value of the force. It is clear that this would not be legitimate if the

weight were sensibly greater or less in one meter than in another of the total height.

To make the thought definite, suppose that 250 kg.-wt. were the value of the weight for the first meter of fall, 255 kg.-wt. the value for the second meter, and so forth, adding 5 kg.-wt. on passing from each meter to the next. Calculate the work for the 6 meters on that supposition.

Secondly, the hammer $H$ (Fig. 47, § 143) is so guided that every part of it is compelled to fall through the same vertical distance. What we speak of as the weight of an object is, of course, distributed in all parts of it, each portion by itself being heavy; and the total weight ($W$) is the sum of elements that we may call $W_1$, $W_2$, $W_3$, etc. Now in a case like that of the bar $BC$ (Fig. 49) turning about a fixed pivot shown at $A$, the parts near $C$ will go up when those near $B$ are going down, and those at $A$ are standing still. If $W_1$, $W_2$, $W_3$ are the weights of these parts, there is no displacement common for all of them when the bar turns. Each must be multiplied by a different height, $h_1$, $h_2$, or $h_3$, in finding the work for that part of the weight. In any such conditions,

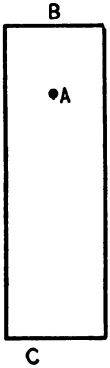

FIG. 49.

$$\text{Total work of weight} = W_1h_1 + W_2h_2 + W_3h_3 + \text{etc.} \quad (22)$$

But where the height through which any part of the body falls or rises is equal to that for every other part, $h_1 = h_2 = h_3$. Write $h$ for this common factor; then

$$\text{Total work of weight} = (W_1 + W_2 + W_3 + \text{etc.})\, h = Wh. \quad (23)$$

The sliding block $B$, and the falling hammer $H$ (see § 143), are intended to realize this simplest kind of displacement.

## THE MECHANICAL EQUIVALENT OF HEAT

**146.** Though the equivalence of work and heat was recognized perhaps forty years earlier, it was not placed on a satisfactory numerical basis until Joule made reliable measurements of the heat-quantity that appears as a result of doing a known amount of work (Ref. 24). The diagram (Fig. 50) applies to his method of experimenting. A heavy piece of metal *M* hangs from a cord that passes over a pulley *P*, and is wrapped around a vertical spindle *S* that is steadied by a rigid frame *F*, and turns freely in the bearings $B_1$, $B$, to pay out the cord as *M* goes down. The spindle is carried through a closed cylindrical vessel,

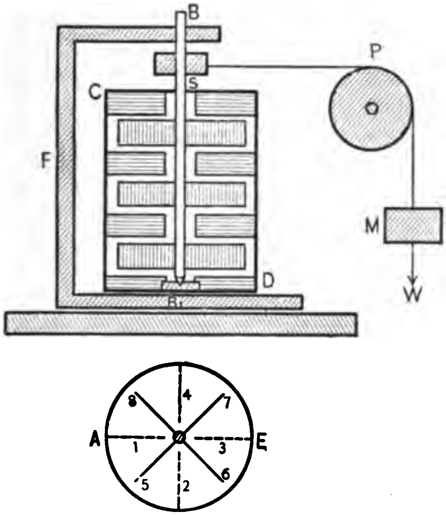


FIG. 50.

shown at *CD* in vertical section, and in horizontal section at *AE*. Inside the cylinder is an arrangement like that found in ice-cream freezers, churns, and other stirrers of liquid or pasty material, where the object is to mix the parts together continually, without setting up any "whirlpool motion" of the contents as a whole. A set of stationary ribs reaches inward from the walls of t

cylinder, while paddles or vanes project outward from the spindle. The ribs are indicated at 1, 2, 3, 4, on the plan, and by the areas with horizontal shading in the section. The paddles are represented by 5, 6, 7, 8, and the areas shaded vertically. The cylinder being filled with water and firmly attached to $F$, $M$ is allowed to descend. As the spindle turns, carrying the paddles with it, the water is caught between them and the fixed ribs, and tossed about or churned. On stopping $M$, and letting the water come to rest, the latter is found to be warmed, and the number of calories corresponding to the rise in temperature can be calculated.

The weight of $M$ being so regulated that it settles into uniform, steady motion downward, the positive work of the weight is just sufficient to offset the negative work of resistances (see § 144). Care being taken to reduce friction everywhere except between the water and the surfaces inside the vessel, the practical consequence is to expend the whole available work on rubbing parts of the water against those surfaces and each other. If the weight of $M$ is $W$ gr.-wt., and $h$ cm. the vertical distance that $M$ falls, the work available is $Wh$ gr.-cm. If $W_1$ gr.-wt. of water are heated, including the "water-equivalent" of the vessel, the paddles, etc. (see § 116), and the temperature is raised from $T°$ to $T_1°$, the number of calories measuring the transformed work is $W_1\,(T_1° - T°)$. The outcome of Joule's elaborate tests under varied conditions was to discover that the quotient $\dfrac{Wh}{W_1\,(T_1° - T°)}$ is always the same number, whose value (corrected slightly by more recent measurements) lies close to 42,800. Since the ratio just written can be regarded as dividing an amount of work

equally among the corresponding number of calories, it expresses the quantity of work equivalent to one calorie, or the **mechanical equivalent of 1 calorie** of heat. Accordingly, 42,800 gr.-cm. is currently known by the (slightly abbreviated) name, the "mechanical equivalent of heat."

## STORED EFFECTS OF WORK: ENERGY

**147.** Two features in the preceding experiment are specially contrived for convenience in controlling the quantities measured: (1) the work is done upon $M$, but the heat appears in the water; (2) the work is changed into heat continuously, as fast as the weight does it, and is not allowed to accumulate as a mechanical effect — more rapid motion, for instance. But it is observed (more broadly) that work and heat can be connected with the same body, the work being done first, and changed into heat some time afterward. The expansive force of the powder-gases does work in a rifle, which, it may be said, is "stored up" in the bullet as it leaves the muzzle, the effects being registered in the great speed attained. This work is dispensed to some extent along the bullet's track, being changed partly into heat as a result of air friction. But on striking a target, the lead is frequently melted by the sudden conversion into heat of the stored work still remaining in the bullet. The same considerations apply in explaining how the water of a stream can be warmed by plunging one or two hundred meters as a waterfall, and striking on the rocks beneath. A rough estimate shows the warming in Yosemite Fall by this action to be something like one degree. A more rapid transformation of stored work into heat, as a conse-

quence of exaggerated air friction, is held responsible for the incandescence of "shooting stars" (meteorites). Careful reflection upon the thoughts connected with Joule's experiments should quicken our perception of many similar results that might pass unnoticed before.

**148.** The idea of transforming work into heat immediately, and the additional possibility of storing work-effects, to be converted into heat later, suggest the need of some one term that can be employed at all stages of the process, to include heat and other measured consequences of work, as well as work itself. The word "energy" is such a term, and every variety of change back and forth between mechanical effect and heat can be compendiously described as a **transformation of energy.** The evident convenience and economy of some general word here are secured when we attach to "energy" this new meaning as a physical quantity. But it is not a misplaced caution, perhaps, to insist once more that physical discoveries are not made by inventing a term, or adding a meaning (see § 34; § 78). The phrases "chemical energy," "electrical energy," and others like them are compact and serviceable, yet they imply no more than the ascertained facts that work, heat, and other measurable equivalents of work are among the possibilities connected with the phenomena classed as chemical or electrical. We may record and even measure the transformations of energy, which cause us to experience such different sensations as light, heat, and electrical shock, though we remain ignorant why those changes occur, and do not know fully in what they consist. In the remaining chapters we shall be able to point out some forms into which energy passes, and to illustrate several rules that can be expressed in terms of it. The conception is espe-

cially helpful in the task set us — that of recognizing unity and likeness in larger groups of phenomena (see § 6).

## COOLING BY EXPANSION: TWO SPECIFIC HEATS OF GASES

**149.** In the steam-engine, it is heat that is supplied by burning fuel, and work that is obtained; the change in form of the energy is the reverse of that which we have been mainly considering. For the better balance of our knowledge in these matters, it will be profitable to take up one or two simple instances where such conversion of heat into work can be observed pretty directly. The universal use of the bicycle pump acquaints us with the heating of a gas as an effect of the work done in compressing it. That a gas can be cooled when its pressure does work during expansion is less likely to attract attention; though the fact is shown if the test be applied properly (Ex. 91).

But if a gas like air is cooled under these circumstances, it follows that a certain quantity of heat must be transferred to the same gas as it expands, if its temperature is to be kept constant. That heat can be termed latent, with the same justice that we speak of latent heat of fusion, solution, and vaporization. Supposing the quantity of heat that disappears to be the equivalent of work evidently done during expansion, we are now in a position to calculate its amount beforehand; we shall then compare the result with observed facts. Let us begin with a liter of air under standard conditions (see § 65, § 107), contained in a vertical cylinder *AB* (Fig. 51), below the movable piston *AC*. The barometer height may be supposed a

little less than 76 cm., the weight of the piston being just sufficient to bring the pressure within the cylinder to the standard value. Assume the piston-area to be $33\frac{1}{3}$ □ cm.; then the original altitude $BA$ must be 30 cm. ($33\frac{1}{3} \times 30 = 1000$ c.c.). The expansion may be produced by heating, as well as by reducing the external pressure; and, the former plan being closer to the line of our present purpose, let the air be heated gradually to 91°, while the piston rises to maintain the pressure constant at one atmosphere. The volume of the heated air will be increased by $\frac{91}{273} = \frac{1}{3}$ of its original value (see § 107); that is, the piston must rise $30 \times \frac{1}{3} = 10$ cm., since the piston-area will not alter appreciably.

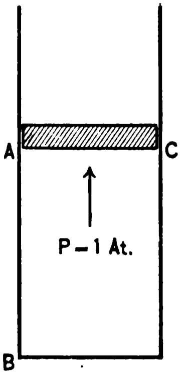

FIG. 51.

The distance through which the force acts is then 10 cm. The pressure upward being 1033 gr.-wt. (on 1 □ cm.), the total force on the lower side of $AC$ is $(1033 \times 33\frac{1}{3}) =$ 34,433 gr.-wt. The work done in pushing the piston slowly up is $(34{,}433 \times 10) = 344{,}330$ gr.-cm., or

$$344{,}330 \div 42{,}800 = 8.05 \text{ calories.}$$

**150.** The next step is to ask: Can these supposed 8 calories of "latent heat" be recognized experimentally? In the first place, accurate measurement of the heat-quantity supplied shows different values for the specific heat of a gas; one when 1 gr.-wt. of it is raised 1° in temperature at constant volume, another under conditions corresponding to our example, when the pressure is constant and the gas expands. Secondly, the specific heat is greater at constant pressure than at constant volume, according to

our expectation. Thirdly, as to numerical comparison for air, the experimental data being: (1) that its specific heat for constant volume = 0.168; (2) that the other specific heat is 1.41 times as large. Under standard conditions, the air in 1 liter weighs 1.293 gr.-wt. At constant volume, the number of calories required to raise that weight of air 91° in temperature is $(0.168 \times 1.293 \times 91) = 19.77$ calories. The *additional* quantity of heat for constant pressure is then, according to observation, $(19.77 \times 0.41) = 8.11$ calories. The calculated value 8.05 calories stands comparison with this very well (Ref. 25). The particular dimensions chosen for the cylinder offer a certain numerical convenience, but they are without influence on the general result, as trial will show.

**151.** There is no doubt about the conclusion to be drawn from the evidence just presented. The eight calories of energy added to the air as heat are passed on immediately as work done in lifting the heavy piston, and crowding back the surrounding atmosphere. When the air in the cylinder cools, the weight of the piston and the atmospheric pressure compress it, and in their turn do work, which is restored and recognized as heat. This part of the energy is not hidden (latent) within the cylinder, but outside it; and its measure, in the form temporarily assumed, is through mechanical effect, not by means of thermometer and calorimeter. The heat that used to be thought of as imprisoned among the particles of heated gas was really escaping and returning in disguise.

Air is a good illustrative example, because the process proves to be transparently simple. The relations are often much more complicated, but the same thought — that heat and work are in various ways interchange

able — puts us on the track of resolving the complications.

What source can you assign for the heat once regarded as squeezed out of iron by hammering (see § 8)?

Since the specific heat of a gas depends upon the conditions under which it is heated, in a way that involves the mechanical equivalent of heat for its explanation, no gases were included in the table of § 117. The specific heats at constant volume for a few common gases are added here. It is remarkable that nearly 2.5 calories of heat are required to raise 1 gr.-wt. of hydrogen 1° in temperature, this being the single known instance of specific heat greater than that of water. The same ratio between the specific heat at constant pressure and that for constant volume does not hold for all gases; but the value 1.4 may be taken for the four gases here named: —

SPECIFIC HEATS (Gases at constant volume)

| | | | |
|---|---|---|---|
| Air. . . . . | 0.168 | Nitrogen . . . | 0.173 |
| Oxygen . . . | 0.155 | Hydrogen . . | 2.411 |

## SOME EFFECTS OF LATENT HEAT

**152.** The answer to the general question about latent heat (see § 141, end) depends upon discovering whether the energy supplied as heat passes into some other form or not. Turning first to water boiling under standard conditions, what account can be given of the 537 calories required to evaporate 1 gr.-wt.? The bulk of the steam formed at 100°, the barometer height being 76 cm., is

1612 times that of the water at that temperature; how much work is done in occupying the increased volume? At 100°, 1 c.c. of water weighs 0.959 gr.-wt., and 1 gr.-wt. of it, therefore, has a volume of 1.043 c.c. The corresponding volume of steam is $(1612 \times 1.043) = 1681$ c.c., or the *increase* in volume is 1680 c.c. The heat-equivalent of the work done in gaining this increase is $(1680 \times 1033 \div 42{,}800) = 40.55$ calories. Explain the last step in detail, using the model of § 149.

The work done in consequence of the external pressure exhausts only a small fraction of the heat supplied; for each gram-weight evaporated, nearly 500 calories remain. If these pass into the form of work at all, that must be done *inside* the water, in tearing the particles asunder. We must halt at this point with calculation; but it is allowable to remind ourselves that water does show cohesion (see § 76), which would call for mechanical effort measurable as work in separating the particles of water. The equivalence of that work to 500 calories for 1 gr.-wt. is left an open question. A similar statement, with a like reservation, can be made in general for evaporation, solution, and fusion. The need of some work (to be supplied as heat) is apparent in such circumstances, because we know as facts: (1) that the particles separated do of themselves cling together; (2) that these processes produce cooling in many cases, if heat is supplied inadequately. But we stop short of asserting that requisite work of this sort — and nothing else — is represented in the heat of fusion, solution, and evaporation.

The particles of gases seem indifferent in certain ways to each other (see § 68). How does the measured equivalence of extra heat and *external* work bear on that subject?

**153.** The most noteworthy instances of heat connected with internal action are found when chemical compounds are formed. Heat to the amount of about 8000 calories appears as a result of burning 1 gr.-wt. of carbon (coke or charcoal) with free access of air. The formation of water from 1 gr.-wt. of hydrogen yields over 34,000 calories. And heat disappears where the processes are of such a nature that compounds break up. Probably it seems easy and natural to extend the thought about heat relations in fusing and vaporizing to chemical action also. Our imagination is ready to see forces pulling the smallest parts of carbon and oxygen together, holding them bound in union, and resisting their separation. If such forces were present, they would do work during combination, which might appear as heat. And in the reversed situation, heat would disappear in proportion as it was converted into work, and applied to tearing the parts away from each other.

But whether those actions proceed in just that way or not, there is no speculation about the quantities of heat which are added to our stock when carbon dioxide (carbonic acid gas) is formed by burning any variety of carbon like coke. This and other common examples of chemical combination are measurable sources of heat which is available to do work; we can reckon on so many calories for each gram-weight burned. In this sense, the uncombined materials are to be included in our supply of energy. The possibilities of work represented in 1 gr.-wt. of carbon amount to ($8000 \times 42{,}800$), or more than $34 \times 10^7$ gr.-cm. The same weight of unburned hydrogen stores (so to speak) over $145 \times 10^7$ gr.-cm. of work, if it could all be utilized.

## RADIANT ENERGY IN SUNSHINE: OTHER INSTANCES

**154.** Among the four sources of heat named at the opening of this chapter, the second and third have now been brought into relation with the idea of energy, and modes of transforming it. The more particular discussion of electrical action from that side must be reserved until we have examined into the special phenomena of electricity; but there is not the same reason for delaying consideration of the remaining source of heat in sunshine, and the transformation of energy that we connect with it as a type.

The remarkable property of sunshine, distinguishing this form of energy from mechanical and chemical action, as well as from heat, is that everything usually classed as substances, materials, or bodies can be dispensed with in conveying it. It crosses freely the most nearly complete vacuum that is producible by any known means (Ex. 92); and the greater part of its track from the sun is, we are led to believe, similarly void. The real significance of this fact, of course, is that the word "vacuum," as a name for a storehouse of energy, should not be understood too literally (see § 14).

Taking polished metal, clear glass, and black felt as examples, we are familiar with three kinds of result when sunshine falls upon objects; it is seen to be: (1) turned aside, or reflected; (2) allowed to pass, or transmitted; (3) obstructed, or absorbed. Transformation of the energy accompanies absorption, giving us heat most commonly, though special consequences, like the chemical actions of photography, appear in some cases; but reflection and transmission leave the energy untransformed

We are naming these three results separately, yet combinations of two, or all three of them, are found in the same substance. Polished metals absorb as well as reflect; they become hot by "lying in the sun." Glass transmits only a fraction of the energy in sunshine to which it is exposed, while it reflects part, and absorbs the remainder. Absorption causes heat, and reflection dazzles our eyes.

The available evidence leads to the conclusion that the sun is a glowing hot body, whose heat-energy is being transformed gradually at its surface, and carried away in all directions as sunshine. Energy in this form adapted for conveyance through a vacuum is called **radiation**; and the sun is said to radiate, in so far as it distributes its stock of energy by this process. According to our view of the situation, the energy of the sun is transferred to the earth, to perform its service in warming sea and land, by a double transformation: (1) from heat to radiation at the sun; (2) from radiation to heat at the earth. Radiation is converted into heat, only to the extent that it is absorbed; our atmosphere (especially the pure air at considerable altitudes), which transmits a large proportion of the sun's radiation, is warmed to a slight degree only by the passage through it of energy enough to evaporate tons of water from the ocean. The local supply of sun's radiation during a known time has been converted into heat and measured with great care, giving about $2 \times 10^{24}$ calories as an estimate of the heat received from the sun annually by the earth. And the earth's disk, we must remember, is so small when seen from the sun, that about $22 \times 10^{8}$ such areas would be required to occupy the complete sphere of the heavens. These numbers are impressive in thinking of the sun's radiation as a source of heat.

**155.** But the sun is not alone in giving off radiation; bodies around us are parting in similar fashion with the energy resident in them as heat, even where the materials are not glowing hot; that is, do not send out radiation which affects our eyes as light (Ex. 93). When such facts as these are duly weighed, they should forestall the hasty assumption that the whole extent of the sun's *radiation* is represented in its *light*, and prepare us to realize that equality of temperature in neighboring bodies is largely due to invisible radiation exchanged automatically among them (Ref. 26).

Discuss the evidence furnished by Experiment 93, and strengthen it from your own observation.

Daily experience teaches that the freedom with which energy is radiated by a given body increases as its temperature is raised. Recall some instances that support this statement. The condition of the radiating body's surface, however, exercises a marked influence, as well as its material and temperature (Ex. 94). But the behavior of materials as regards radiation given off, or that received from various sources, is one of their special and "individual" properties, concerning which few general rules can be stated, and observation is the best guide. Such peculiarities are sometimes of great advantage in establishing the artificial conditions of civilized life. For example, both glass and water-vapor, through which *light* passes with small absorption, obstruct very noticeably the radiation proceeding from the warmed soil of a greenhouse, and from the stoves or fireplaces of our rooms. A space where the humidity is large, and which is covered with a glass roof, constitutes, therefore, an effective "trap" for heat derived from the sun.

## CONVERSION OF ENERGY: PARTIAL SUMMARY

**156.** Conversions of energy into the form of heat, and out of it, are brought before us daily in many ways. A steam-engine offers examples of them in its fire-box where the fuel burns, its boiler where the water is evaporated, its cylinder where the expansion takes place, and the condensation of the exhaust steam (Ref. 27). Food is largely a fuel, whose combustion by physiological processes sustains the activities of animals. The cooling of air in rarefying, as it passes to upper levels of our atmosphere, is not to be neglected among the causes of clouds and rain. The adjustment between radiation received from the sun, and that given off by the earth's surface, is on the whole the largest factor in determining climate and the seasons. The habit of giving attention to such matters will strengthen our grasp on these ideas, especially if we learn to look deliberately for the points at which transformations of energy occur. By way of summary at the present stage, it may prove helpful to make a group of four types, that are met again and again as phases of changes in energy: —

(1) Energy is stored as mechanical effect in the visible motion of a body, and converted more or less gradually into the equivalent quantity of heat.

(2) Heat disappears in producing or maintaining such visible motions.

(3) Heat appears by realizing possibilities that have been prepared beforehand, and which consist either in the situation of a body, or in the relation of bodies (or substances) to each other.

(4) Heat disappears in preparing such possibilities.

Gather instances to compare with these statements.

TRANSPORT OF HEAT: CONDUCTION AND CONVECTION

**157.** At several points already we have touched upon the transportation of heat from place to place, to an extent which leaves but little to be done in completing the necessary account of the ways in which that may happen. We shall begin to supplement what has been said, previously, by noting explicitly a broad distinction in the phenomena exhibited between the effective source of heat and the objects heated. In some cases, heat is recognizable as such everywhere along the route; in others, a different form is assumed by the energy in transit. The second mode of conveyance is the main theme of this chapter, and has been discussed sufficiently. As regards the first alternative, one instance of this type is found in a hot poker, or in the stove itself. If the metal becomes heated in its extreme parts, it is hot to the touch at all intermediate points. A second example is seen in any system of heating by means of water or air that circulates between a furnace and the rooms of a building; heat is sensibly present all along the pipes. When this method of heating is resorted to with either solids or fluids, the heat is handed on by repeated transfers at a series of contacts. But the particles of metal are arranged in permanent order; they can part with heat only to the neighbors assigned them. A particle in a fluid, on the other hand, can move through considerable distances, and, according to circumstances, either distribute its charge of heat gradually over the whole length of its track, or bestow the greater part of it at one place. What we observe, both in solids and in fluids, when heat is thus transferred at contacts, is often described as a "flow" or "stream" of heat. But the flow is *through* the

stationary material of a solid; and it is associated *with* a stream of particles in a fluid. The name applied to the former process is **conduction,** the latter being known as **convection.**[1] The difference between the two is scarcely essential; "convection currents" (see § 99) become prominent, *after* the mobile particles of the fluids have been heated locally by conduction, as a result of the changes produced in specific weight. If special precautions are taken to prevent such currents, a flow of heat can be maintained through liquids, at least, and they conduct like solids (Ex. 95). Substances differ remarkably in the rate at which they conduct heat, and are classed as good or bad conductors accordingly. Liquids (except mercury and other molten metals) rank with bad conductors among solids. The *conduction* of heat in gases is hardly observable. In the list below, each substance is a better conductor than the ones that follow it; brackets mean approximate equality; and the lines mark great differences between the groups which they separate.

CONDUCTORS OF HEAT

| | | |
|---|---|---|
| Silver | German silver | Glass |
| Copper | Mercury (liquid) | Wood |
| ——— | ——— | Paraffine |
| Iron | Marble | Paper |
| { Lead | Ice | { Flannel |
| { Platinum | Water | { Silk |

**158.** Several modes of conveying heat are frequently combined, and determine the stationary temperature, the net

[1] Consult the dictionary for the etymology of this word.

gain, or the net loss observed in processes of heating and cooling that occur in nature, or are carried on artificially. We should learn to realize how common phenomena of this kind come to pass, by watching the conditions that shape them; and as a first instructive example, we may take the deposit of dew. When the water-vapor of the atmosphere has reached the temperature for which its actual vapor-pressure is a maximum, it begins condensing if cooled further. As the temperature falls, the allowable maximum is lowered faster than the pressure of the water-vapor would be diminished by cooling (see § 109); part of the relief must be provided by condensation. Thus the maximum pressure falls from 1.3 cm. of mercury at 15° to 0.9 cm. at 10°. But the diminution due to cooling alone would be only about 0.02 cm. Clouds and rain are one form of the result, or the change may go on under a clear sky at night, leaving dew as the visible product. An unclouded sky is favorable to losing heat as radiation from the earth's surface; it is a well-known practice to mitigate local frosts, and consequent injury to fruit, with smoke-clouds from burning straw. But the loss of heat at the surface may be made good in part by conduction from the soil below, and the net loss will be greatest for objects that radiate well, and conduct badly.

How does this point to a reason why dew should not form so freely on rock or metal?

The local cooling of the water-vapor is most effective if it is not stirred, either by wind or by convection currents, and thus averaged in temperature with warmer portions. Connect this condition with the fact that heaviest dew is seen near the ground, and after still nights (see § 8).

How do you explain the frosting of window panes in winter?

Show that conduction, convection, and radiation all enter as elements in warming a room by means of a fire in a stove. Would you say that the relative importance of radiation is changed when an open fireplace is substituted for the stove?

An open vessel of water is heated over a small gas-flame, and reaches a stationary temperature short of boiling. What becomes of the heat supplied?

In order to economize fuel, which part of a tea-kettle should be kept bright? Which part should be a good conductor?

How do you account for the effectiveness of fur and feathers as "protection against cold"?

When wood and iron are actually at the same temperature, why does the wood seem warmer to the touch than the iron at 0°, and cooler at 150°?

What properties of mercury that you know favor its use for thermometers, in comparison with water or alcohol? Do you recognize points in which the other liquids surpass mercury?

In producing a *sensation* of heat or cold, how does the great specific heat of water offset in part its feeble conducting power?

# CHAPTER X

## WORK AND ENERGY. FURTHER APPLICATIONS

**159.** We have introduced the ideas of work and energy in connection with heat and its transformation, but they present themselves in every part of Physics, and we have to consider next their application to the range of phenomena included in Chapter II and Chapter III, with the intention of using this material as a preface to other matters of similar nature.

### CHANGES OF POSITION, AND WORK OF WEIGHT

If we return to any instance of buoyancy, and examine the conditions under which a homogeneous body rises or sinks through a fluid, it is plain that such readjustments always happen, as correspond to getting all the (positive) work done by weight that is possible in the circumstances, taking fluid and immersed body both into account (see § 33). Let *ADC* (Fig. 52) represent a vessel of liquid, *B* a ball of homogeneous solid in its original position. If *B* is specifically heavier than the liquid, and sinks to B″, that is equivalent to

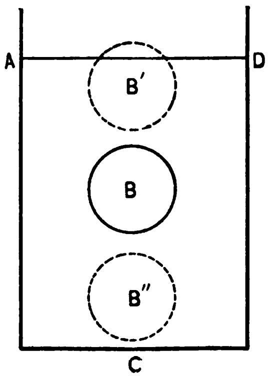

FIG. 52.

an exchange of places with an equal sphere of liquid which was originally at $B''$. Positive work is done by the weight of the solid, that done by the weight of the liquid as it is lifted is negative, and the former exceeds the latter. These relations are reversed when the solid is specifically lighter. The ball is forced up, say to $B'$, an equivalent volume of liquid descends to $B$, and the positive work is again greater. Where the specific weights of solid and liquid are equal, there is nothing in the way of work to be gained by displacement, and none occurs.

Supposing that the same ball $B$ is placed at rest on a horizontal table, it will show no preference for any particular position. If the ball is rolled, no work is done on the whole by its weight, since each part that goes down is paired with an equal part that rises through an equal vertical distance. But if $B$ were a ball made up of two hemispheres, one of zinc and the other of lead, and were placed at random on the table, the effort to bring all the lead lower than any of the zinc would be unmistakable. Here, too, the weight will do so much work as the conditions permit, giving lead the monopoly of the lowest positions.

**160.** The contrivance traditionally known as a "wheel and axle" serves as a third example to illustrate these thoughts (Ex. 96). We shall satisfy ourselves that the condition of balance for the two weights pulling downward at the circumferences is expressible in the same terms as before: the positive and the negative work must just offset each other, if the wheels be turned. Notice, in the first place, that the weight of the wheels themselves does no work on the whole, the relations in this respect for them being entirely similar to those of a ball rolling

on a horizontal table. Secondly, using the letters of the diagram (Fig. 53), experiment shows directly $\frac{W_1}{W} = \frac{R_2}{R_1}$. But the vertical distances $D$ and $D_1$, through which $W$ and $W_1$ act, are lengths of cord taken up and paid out, corresponding to arcs of sectors with radii $R_2$ and $R_1$. The central angles of the sectors must be equal, because the wheels are fastened together and turn as one. Consequently, as the study of geometry has taught us, $\frac{D}{D_1} = \frac{R_2}{R_1}$, and, finally,

$$\frac{W_1}{W} = \frac{D}{D_1}; \quad W_1D_1 = WD. \quad (24)$$

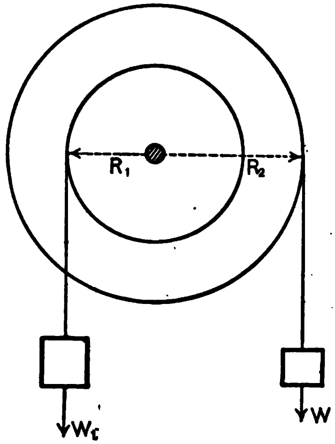


FIG. 53.

When the ratio of the weights is not equal to the inverse ratio of the corresponding radii, do the wheels turn so that positive work is done to the greatest extent possible in the circumstances?

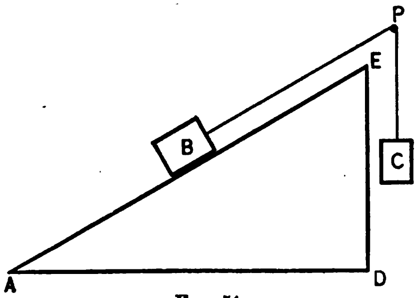


FIG. 54.

The blocks $B$ and $C$ (Fig. 54) are supposed to be in a condition of balance, the former resting on the "inclined plane" $AE$, the latter hanging free, while they are connected by

a cord that passes over a fixed peg $P$. The part $BP$ of the cord is parallel to $AE$, and the part $PC$ is of course vertical. In this contrivance it is evident that the weight of $C$ acts through a vertical distance equal to $AE$, when that of $B$ acts through a vertical distance equal to $ED$. And further, for any motion of $B$ along $AE$, the ratio of its vertical displacement to the corresponding one for $C$ is $\frac{ED}{AE}$. Show that the conclusions from your experimental results (Ex. 97), where friction is allowed for, could be anticipated by applying the same rules about work that we have found to hold in the three preceding instances.

## CENTRE OF WEIGHT

**161.** The discussion has been carried to this point without departing from the three conditions that are emphasized in § 145 as being the simplest for the measurement of work. It is an easy matter, however, to express the work of weight in the broader case where a solid body turns as it moves, so that its parts do not all rise or fall through equal vertical distances. We shall now endeavor to gain that extension of scope for our rules concerning work; and we take the first step by putting this definite question: When some parts of a solid body move down (or up) more, and some less, what point of the body is it whose change of level, multiplied by the (total) weight, gives the actual value of the work done by that weight? In other words, what point shows the *average* vertical displacement for the whole body? Since, from the very form of the question, if $W$ is the total weight, and $\bar{h}$ the vertical

distance that we seek, the statement in symbols follows (see § 145, Eq. (22)),

$$W\bar{h} = W_1h_1 + W_2h_2 + W_3h_3 + \text{etc.} \tag{25}$$

And the meaning attached to $\bar{h}$ agrees with the notion underlying "average" from the first introduction of it (see § 43). The average point (in this sense) for weight shall be called the **centre of weight.** Now if the weight of a body causes it to turn about a fixed axis, the greatest possible amount of (positive) work will not be done until the centre of weight is in its lowest position, vertically below the axis. Because, whatever position the body starts from, the fact that positive work is done must mean that the centre of weight moves to a lower level (see § 145, beginning); and more of it will be done so long as the centre of weight continues to approach the lowest point that it can reach. Therefore, if we contrive that a body shall be free to turn about an axis (conveniently a horizontal axis), and settle into the position assumed under the influence of weight, we may expect to find the centre of weight in the vertical plane passing through the axis. This consideration opens one way to locate the centre of weight experimentally (Ex. 98).

**162.** The above method, applied to homogeneous solids in the form of blocks (rectangular prisms), cylinders, and spheres, identifies the centre of figure as the centre of weight for them; a result agreeing with our view of the latter point as representing an average for the entire body, since every line that can be drawn through the centre of figure in such solids is clearly bisected there. The average for a pair of *equal* particles lies half-way between them. Taking pairs equidistant from the centre of figure, that

point is the average for each pair singly, and consequently for the entire block, cylinder, or sphere, which can be built up of such pairs. If solids in these forms are not homogeneous, the particles equidistant from the centre of figure are not always *equal in weight*, with respect to which the average is taken, and therefore this idea ceases to apply.

When the centre of weight has been discovered, the weight of the body should show no tendency to turn it about any fixed axis passed through that point; because the centre of weight cannot be moved up or down by that kind of turning, and, without such change of level for the centre of weight, no work can be done by weight, according to our fundamental supposition about the matter. The centre of weight, if properly located by experiment, is found to meet this test; bodies "balance" when the axis passes through it.

As a help toward realizing that the work of weight is expressible as $W \times \bar{h}$ gr.-cm., however a body turns and twists, and falls or rises, notice that any actual change of position can be thought of as produced in two distinct stages: —

(1) Hold the centre of weight at its original place, and turn the body (with a ball-and-socket motion) until every line and plane becomes parallel to its final position. This is always possible, as trial will prove.

(2) Keep the body thus "parallel" and move it, completing the displacement. In this stage all parts move through equal distances along parallel lines.

During stage (1) no work is done, since the centre of weight is held at rest. In stage (2), the centre of weight takes part in the equal parallel displacements, and it is

then proper to multiply the total weight $W$ by the *common* vertical distance (see § 145, Eq. (23)), giving $W \times \bar{h}$ gr.-cm. for the work done by the weight. The stages here supposed to be successive are really simultaneous, but that does not affect the quantity of work. The diagram (Fig. 55) shows how such a scheme can be executed in a plane with a rectangle $ACB$, of which $C$ is the centre. Turning about an axis at $C$ brings $AB$ to the position $A'B'$, and the "parallel motion" carries it to $A''B''$; all lines like $A'A''$, $B'B''$, joining corresponding points are equal and parallel. This illustration in a plane should be supplemented by studying the relations with a solid object.

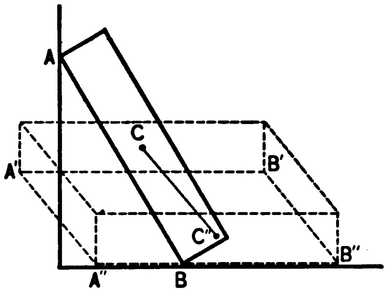

FIG. 55.

It is implied everywhere, in what we have said about centre of weight for a solid, that it does not need to be located afresh when *external* conditions change. It is, for example, in the axis of a given homogeneous cone, at the same distance from the vertex, whether the cone stands on its base, or lies on its side, or rolls. The situation of the centre of weight with respect to the body is as permanent as the distribution of weight upon which it depends.

Is this taken for granted as a fact in Experiment 98? Do the experimental results justify the assumption?

Give some instances where the centre of weight is situated within a hollow space, and not in the material of a body.

**163.** One advantage gained by introducing centre of weight is the addition thus made to our resources in dealing with weight distributed through all parts of a body. In order to illustrate that point, and to render the useful idea of work more familiar, some simple problems are inserted here. But, before entering upon the discussion of them, it should be announced explicitly, perhaps, that centre of weight is important chiefly as a convenience in calculation. Take care to observe the express limitation in the statement, "The measured work of the weight is the same *as though* the whole weight acted at the centre of weight." The real distribution of weight is untouched by our fictitious concentration of it at a point.

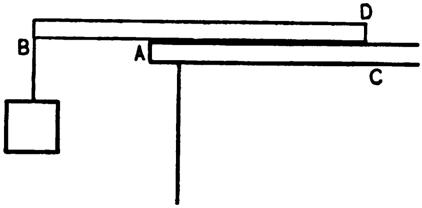


FIG. 56.

A uniform bar $BD$ (Fig. 56) is 3 meters long, and each centimeter of its length weighs 50 gr.-wt. It rests upon a horizontal table $AC$, and from its projecting end is hung a load of 5 kg.-wt. How far beyond $A$ must $B$ project, in order that the bar may just begin to turn on the edge at $A$? Compare this with the wheel and axle in § 160.

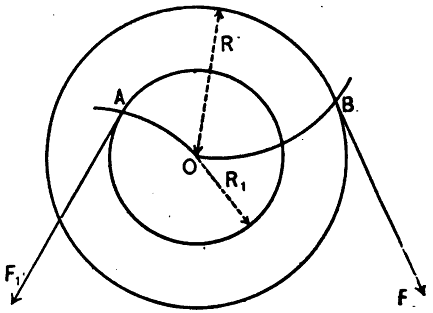


FIG. 57.

The cords $A$ and $B$ (Fig. 57), on a wheel and axle with

*vertical* axis, are pulled in the directions shown, and the wheels do not turn. Compare the ratio of the forces $F$ and $F_1$ with that of the radii $R$ and $R_1$. If the wheels are cut away, leaving only the bent bar $AOB$ pivoted at $O$, will the balance be disturbed if the cords attached at $A$ and $B$ are pulled just as before?

## LEVERS

**164.** The diagram (Fig. 58) represents the essential elements of various contrivances to which the name **lever** is applied. Three forces, $F_1$, $F_2$, $F_3$, act perpendicularly to a rigid bar $ABC$, one of them being supplied practically through a fixed support equivalent to a pivot, and known as the fulcrum. In a wheelbarrow, the fulcrum in the wheel-axle might be $A$; the balance has a fulcrum situated like $B$. The forces applied to a lever may be due to weight, muscular effort, or mechanical devices, but they are for the present considered to be parallel. $ABC$ may represent a real bar, or only a line drawn through the fulcrum and perpendicular to the forces, while the real lever-bar is shaped as shown by the dotted lines (taking $B$ as the fulcrum). The conditions of balance shall be considered, first without paying attention to the weight of the lever-bar itself.

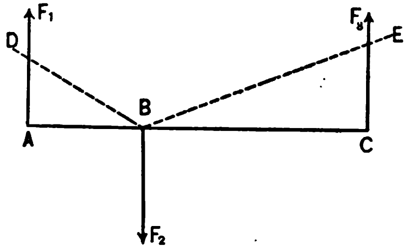


FIG. 58.

Assume the fulcrum at $A$, at $B$, and at $C$ in succession,

and express the conditions of balance as regards turning about the several points, comparing each case with a corresponding arrangement in the preceding problem, contrived by unwrapping the cords, and changing the directions (not the magnitudes) of $F$ and $F_1$ (Fig. 57).

When the bar is balanced, the equation $F_2 = F_1 + F_3$ holds for the magnitude of the forces, whichever point represents the fulcrum (Ex. 99). With this relation among the forces, no positive work would be done in pulling the bar away from the fulcrum bodily, and that does not happen. The whole lever would move in the direction of $F_2$ or of $F_1$, if $F_2$ were greater or less than the sum of the other forces. Consider the evidence of the experiment carefully; and notice that a bar with balanced loads at $A$ and $C$ can be lifted (still balanced as regards turning) by a loop at $B$, if the force applied there exceeds the sum of the weights.

In determining whether a lever will turn or not, one important element, as we have found, is the perpendicular distance from the fulcrum to the line in which the force acts. This is called the **lever-arm** of the force. Where the lever-bar is bent, like $AOB$ (Fig. 57) or $DBE$ (Fig. 58), the lever-arms are still measured perpendicular to the forces, being $R$, $R_1$ in the first case, $BA$, $BC$ in the second. The product of a force by its lever-arm, which occurs frequently in such problems as these, is known as the **moment** of the force; evidently it depends upon the fulcrum chosen. From the results already obtained for the wheel and axle and the lever, verify the following rule: When no turning takes place, the forces that would turn the body in opposite directions on the axis have equal moments.

Extend the statement about moments to the case where

the forces acting are not parallel (see Fig. 57, § 163), and the weight of the lever-bar is taken into account (see Fig. 58, § 164).

Collect a dozen instances of levers among the familiar tools, and the mechanical contrivances in daily use. Select some in which there is gain of force, and some in which there is gain of distance or speed. Is any work gained by leverage?

## POTENTIAL ENERGY

**165.** In the practical matters of life, a considerable share of the work done is devoted to raising heavy materials above their original level. Water is pumped from wells to the surface of the ground, or from the surface into elevated tanks and reservoirs; coal and ore are brought out of deep mines, grain is stored in tall warehouses, brick and stone are lifted into place in building. The list of appliances for such purposes is a long one: pumps, hoisting-engines, elevators, cranes, derricks, and the rest. A change of level is often the end sought, and is intended to be permanent, as in erecting buildings; or it is merely incidental to transportation, as in loading ships and cars. But it is sometimes one phase of a wider plan, which includes return toward the first level and repayment of the work invested, either directly in the form of work, or else through some equivalent quantity of energy. Instances of the last character are to engage our attention more particularly here. They are before us on a smaller scale when we wind up a clock-weight, and raise the hammer of a pile-driver, in order that work may be done as they descend, which keeps the clock going, or finally drives the pile. The sun operates on a large scale in feeding the sources

of our rivers with water evaporated from the ocean, and thus furnishing "water-power" for mills and factories, as that water returns to its original level. In every such case the work first done by one agency (the hand, the hoisting-engine, or the sun's radiation in the examples quoted) provides the condition that makes it possible for another agency (here weight) to do work on the return.

Regarding a charged air-rifle, a wound watch-spring, and a "set" steel trap as further illustrations, what agencies in each case bring about the direct and the reverse action?

The possibility of getting work done during the second part of such complete processes is regarded in advance as a capital of energy at the beginning of that stage, and put on an equality with unburned fuel in the presence of air, or a loaded cartridge, as representing a supply of work or heat upon which we can draw. As a distinction from work already done, and its consequences that are realized, work still to be done and consequences yet to be furnished are called **potential energy**; the idea that it represents *possibilities* is conceded in the word "potential."

Now accidents may baffle our calculations of potential energy, if we extend that term to cover all such instances as those named above. Wet gunpowder is useless; compressed air leaks out occasionally, or decreases in pressure by cooling; a coiled or bent spring can break, or lose its stiffness by heating. But the work that the weight of a body will do when its centre of weight descends to a given level can be counted upon with certainty; to that extent the automatic arrangements in nature surpass the artificial ones. And if we are to think of potential energy as work (or its equivalent) that must be furnished *inevitably* under circumstances that we control, weight is the better example.

## EFFECT OF WEIGHT DURING FREE FALL

**166.** When a body falls under the influence of its weight, the effect of increase in the work that has actually been done shows itself in the increasing speed with which the body moves. We are now to establish a measured relation between the work done and the speed attained, on the supposition that the body falls from a state of rest, and that weight alone acts. This means, among other things, that the buoyancy of the air and its resistance to motion through it are small enough in comparison with weight to be left out of consideration. That condition is satisfied fairly by substances of greater specific weight, like lead or iron, especially if shaped into balls. But balloons rise, and feathers float slowly downward, unless a vacuum has been produced round them.

Observations made at the same locality, of the time required to fall freely through different distances from rest, indicate that there is a constant ratio between the distance fallen and the square of the time taken in falling, which is the same for all materials, and for bodies of different weight, provided, as we have just said, that the conditions are sufficiently near to those in a vacuum (Ex. 100). If the vertical distances are measured in centimeters, and the corresponding times are expressed in seconds, the value of the ratio is close to 490. Double that ratio, which happens to be more important than the ratio itself as a physical quantity connected with weight, is universally denoted by the letter "$g$." Recording the facts in symbols, and writing $h$ for vertical distance fallen, $t$ for time, we have

$$\frac{2h}{t^2} = g \, [g = 980, \text{ nearly.}]. \qquad (26)$$

**167.** Knowing the distance between two stations, and the time spent by a train in running from one to the other, the distance divided by the time shows the speed at which the train travels. In the usual case the speed is not uniform during the run, and the quotient of distance by time then gives an average of speed (see § 43). We shall apply this idea of average speed to a falling body; but, consistently with measuring distances in centimeters and time in seconds, speed will be reckoned by the number of centimeters travelled in one second, not as kilometers (or miles) an hour, nor as feet a minute (or second). Since the time of fall is $t$ seconds in our notation, when the distance fallen is $h$ centimeters, the average speed for any such time is $\frac{h}{t}$ centimeters a second. But, on looking at Equation (26) we see $\frac{h}{t}=\frac{gt}{2}$. The average speed for the first second is then $490 \times 1$, because $\frac{g}{2}=490$; it is $490 \times 2$ for the interval extending through the first two seconds, $490 \times 3$ for the first three seconds, and so forth, growing uniformly with the number of seconds, counted from the start to the lower end of $h$.

Therefore the new values of the speed, included by adding a second to the time of fall, are large enough to raise the level of the average obtained without them by an equal step (*i.e.* 490), whatever be the number of seconds in the interval. Without the tenth second, the average is $490 \times 9$; with it, the average is raised to $490 \times 10$ for *each one* of ten seconds, not for the tenth second alone. And the addition within *each second* of the interval could not be 490, independently of the number of seconds, unless the amount added were multiplied in proportion as the interval

lengthens, over which the new values are distributed in the process of averaging or equalizing.[1] This reasoning leads to the conclusion that the speed attained by a body falling freely from rest must grow uniformly with the time that has elapsed since it started, becoming five times as great by the end of the fifth second as it was at the end of the first, doubling the value for five seconds by the end of the tenth second, and so forth. But with uniform growth, the average is the half sum of the extreme values at the beginning and end of the interval (§ 43, triangle). And the speed at the start being zero, the speed at the end of the first second must be ($g = 980$), since $\frac{0 + 980}{2} = 490$. Then the speed being multiplied in proportion to the number of seconds, as we have just seen it must be, its value at the end of the second, third, fourth second is $2g$, $3g$, $4g$. In general, if $v$ is the speed with which the body passes the lower end of the distance $h$, after falling $t$ seconds from rest, $v = gt$. This rule of uniform increase in the speed of a falling body was discovered by Galileo, whose work marked the opening of a new era in Physics, by introducing and encouraging the spirit of experimental inquiry (Ref. 28).

## KINETIC ENERGY: WASTE OF ENERGY

**168.** We are now within reach of the relation between work and speed, mentioned at the beginning of § 166. From the equation $v = gt$, applying to a body that falls

[1] NOTE FOR THE TEACHER. — This necessary relation between the law in the series of values averaged, and that in the average obtained, is not difficult to see, if it is illustrated (orally) with particular numerical instances.

from rest, weight alone acting, it follows that $t = \frac{v}{g}$; and, substituting that value for $t$ in Equation (26), we obtain the expression,

$$h = \frac{gt^2}{2} = \frac{g}{2}\left(\frac{v}{g}\right)^2 = \frac{v^2}{2g}. \qquad (27)$$

But the work done by the weight $W$ of a body that falls through a vertical distance $h$ is $Wh$ gr.-cm., where the displacement $h$ is common to all parts of the body, as we shall now suppose it is. Consequently, on multiplying both sides of Equation (27) by $W$, the relation sought between work and speed is found to be

$$Wh = \frac{Wv^2}{2g}. \qquad (28)$$

If the body to which this equation applies were thrown vertically upward with equal speed $v$, how high would it go above its starting-point, before it stopped?

The effects of work accumulated in a moving body are called its **kinetic**[1] **energy**. In the case before us, this positive store of work, which can be drawn upon in various ways, represents the realized possibilities of the potential energy. As the body moves up and down between the levels $h$ cm. apart, it has nothing but possibilities of work at the top, full realization at the bottom, and a combination of the two at any intermediate point. Energy in these two forms may be likened to bank-drafts and money. Potential energy being "cashed" gives us available funds as kinetic energy; and, if we have no other use for the latter at the moment, it may be "invested" in potential energy again by allowing the body to move upward. The

[1] Observe the suggestion in the etymology of the word.

figure of speech remains a fair parallel if continued farther, for we pay "exchange" at each conversion of energy back and forth. The full equivalent of potential energy is not *available* in the kinetic form, because part leaks away from our control in overcoming air resistance, producing heat shown after the "shock" of stopping, etc. This kind of leakage is repeated as the body goes up, and the potential energy again falls short of the amount represented by $\frac{Wv^2}{2g}$ when the body leaves the lower level.

After a clock-weight has been wound up, and provided with a capital of potential energy, the clock goes till it runs down. What forms of work or heat can you name, upon which that capital is gradually expended? Are they further available for our uses? Considering the pendulum of the clock alone, point out in detail how its energy alternates between the potential and the kinetic form, during each swing.

The water in a lake, perhaps 200 meters above sea-level, represents a quantity of potential energy. What transformations of such energy does your experience suggest as frequently occurring, when the water flows down a stream-bed to the sea? When the equivalent of this water and its potential energy is restored to the lake as rain, what source of energy is drawn upon in the process?

In the use of a pile-driver, what other forms of heat or work, besides driving the pile, account partially for the realized potential energy of the hammer?

Add another example, from your experience, of potential energy transformed and escaping us.

**169.** We should not have dwelt at such length upon these various changes in form of energy, if they did not

affect our lives practically in many important ways. The phrase **transformation of energy**, so prominent in this connection, is intended to convey the definite thought that the *same quantity* of energy can go through a series of forms, being only *differently measured* in the several stages. That is, if we are called upon to provide energy as heat, mechanical effect, and so forth, we must get it somewhere; we can change its form (within certain limits), but cannot make it. Everything that goes on around us points in the direction of this conclusion, if rightly considered.

But the further fact is equally vital, that energy, though unaltered in total amount, is continually passing out of control and becoming useless to us. The preceding questions are meant to teach that lesson, which is repeated everywhere. It is like carrying water in a leaky pail; the total quantity of water does not decrease, but what sinks into the ground may be lost to us. We are drawing upon other resources of energy as we do upon our coal mines and forests, converting a part to use, and unavoidably wasting the remainder. There is **conservation of energy**, in so far as it remains unaltered in the aggregate, after taking account of leakage by radiation, by conduction of heat, and in other ways. There is also a costly **dissipation of energy** implied in the fact that those leakages exist (Ref. 29).

**170.** The factor $h$, in Equation (28) (§ 168), reminds us that potential energy depends upon how far the body is to fall, and not at all upon where it is, except that its present position has something to do with how far it *can* fall before reaching an assigned level. The height $h$ is always a *difference* of level; height above the earth's surface in the common case that a body falls to the ground;

but an object at the mouth of a mine-shaft or well has potential energy with reference to their lowest levels, and the ground-level might then be the upper end of $h$. This sort of dependence upon particular suppositions about the future is characteristic of potential energy. Kinetic energy is not thus contingent; the stock of energy is $\frac{Wv^2}{2g}$ at the moment, without regard to how it was obtained, or the manner in which it is to be used.

A train of 200 (metric) tons-weight, running at a speed of 36 kilometers an hour, represents kinetic energy calculated as follows: —

$$W = 200 \times 1000 \times 1000 = 2 \times 10^8 \text{ gr.-wt.}$$

$$v = (36 \times 1000 \times 100) \div (60 \times 60) = 1000 \text{ centimeters a second.}$$

$$2g = 2 \times 980 = 1960.$$

$$\frac{Wv^2}{2g} = \frac{(2 \times 10^8) \times (1 \times 10^6)}{1960} = 102 \times 10^9 \text{ gr.-cm.}$$

Notice that all forms of energy are frequently measured in gram-centimeters, because they are equivalents of work, and of the same kind as work.

The kinetic energy of this train is the same, whether the speed is gained by pull of the engine on a level, or by running on a down grade with steam shut off. And when once acquired in either way, the kinetic energy may be applied in climbing a grade, or in grinding the brake-shoes to slacken speed and stop, or in wrecking another train by collision.

Assuming that 1 gr.-wt. of coal burned in the fire-box yields $2 \times 10^7$ gr.-cm. of work under practical conditions, about $\frac{1}{17}$ of the full equivalent (see § 153), how much

coal does it cost just to get up a speed of 54 kilometers an hour in a train of 180 (metric) tons-weight (saying nothing about resistances to be overcome)?

A vertical shaft 3 meters square and 30 meters deep is half filled with water. How much work is done in raising the water to the surface (see § 161, § 162)? A pump delivers the water steadily from an opening whose area is 100 □ cm., and clears the shaft in 3 hours. How much kinetic energy is wasted in the water discharged?

## HORSE-POWER

**171.** In practical affairs, the length of time required to accomplish a given task enters into our judgment upon the effectiveness of a man who works either with his hands or with his head. Time is an equally important element in connection with the measured mechanical work of which we are speaking here. A mechanical engineer is called upon to design engines that will drive a steamship at 15 or at 20 knots (*i.e.* a certain number of kilometers) an *hour;* or a sawmill with an output measured as so many thousands of feet of lumber a *day;* or a pump whose capacity is stated in terms of the amount of water raised to a given height and delivered in an *hour*. In order to make comparisons on this basis, a standard rate of turning out work has been adopted, which is $75 \times 10^5$ gr.-cm. a second. This is the **horse-power** so frequently named in describing engines or machines. A steam-engine working at 10 horse-power is doing $10\,(75 \times 10^5)$ gr.-cm. of work a second in driving the dynamos, or lathes, or saws, or other machines that are attached to it. The term "horse-power" records the historical fact that

this amount of work a second was originally estimated to represent the average performance of a horse working under favorable conditions.[1]

In the last example of § 170, calculate the number of horse-power utilized in the pump.

A train is pulled steadily along a level track at a speed of 54 kilometers an hour, all the resistances overcome being equivalent to a force of 750 kg.-wt. Calculate the number of horse-power furnished by the locomotive (see § 144, end).

## THE TWO FACTORS IN WEIGHT

**172.** In the course of one second, the pull of its weight upon a body gets up a speed of about ($g = 980$) centimeters a second, starting from rest. If the weight pulled harder, an equal speed would be attained sooner by the same body, and greater speed would be produced in it by the end of the first second; if the pull of the weight were not so great, its visible effect in getting up speed would be weakened. With this thought in mind, it seems natural to look upon the observed value of $g$ as a measure of the weight's influence — which is just what Galileo proposed to do. If it was found that $g = 872$ at one place, and $g = 981$ at another, we should then say that the comparative strength or intensity of the weight at the two localities was in the ratio of eight to nine ($\frac{872}{981} = \frac{8}{9}$). Now Galileo's experiments suggested that $g$ has the same value for

[1] The number given in the text defines the so-called "metric horse-power." When work is measured in foot-pounds (see § 143), the horse-power corresponding is described as 550 ft.-lbs. a second, whereas the metric horse-power is the equivalent of about 540 ft.-lbs. a second. The difference arose from the effort to secure numerical convenience; 75 is an easy number to multiply or divide by.

all materials at the same place (in a vacuum), and more precise measurements carried out since his day have confirmed that conclusion. And this fact, that the result is entirely independent of the material with which the trial is made, inclines us still more to adopt $g$ as an index of how strong an influence the earth exerts, or is ready to exert. Any variation in $g$, such as we have supposed above, would then be due to a change in the *earth's* share of the effect called weight; the bodies affected might be identical in the two places, being transported from one to the other. Thus we should be led to recognize two independent factors in the force called weight; one associated with the body itself, and a second contributed by the earth as a source of the influence, which would be associated with the value of $g$.

## LOCAL VARIATION OF WEIGHT. GRAVITATION

**173.** The first factor presents itself instinctively in thought and speech, — the weight is the "weight of the body," attributed to the body, and depending upon its size and material. But is there any evidence that $g$ varies in value on the earth's surface, marking a different pull on the same body; *i.e.* an independent share of the earth in the result? It is now well known that the values of $g$ obtained from observation are not the same everywhere on the earth, even at the sea-level, after making allowance for every disturbing element; they indicate a range from ($g = 978$) to ($g = 983$). Within the zone of the northern hemisphere, however, where the great centres of civilization are situated, neither of the extremes is reached; to the nearest whole number, the values are grouped almost

entirely between ($g = 980$) and ($g = 981$). Since this is a variation of only about $\frac{1}{10}$ of one per cent, it is allowable to call weight a constant force, as we have been doing (see § 52, end); but the instructive suggestion is left, that weight is a partnership effect in which earth and body are both concerned, and in which either partner can increase his holding independently of the other. The strengthened grip of the earth upon the same body is shown by the power to get up speed in it faster—by an increased value of $g$, the speed added in a second.

It was not until observations chanced indirectly to include a station near the equator, that the variation in weight of the same body became known. In the interest of some astronomical work, a clock that kept correct time at Paris was taken to Cayenne in French Guiana, and was found to lose over two minutes a day there. The change was not due to injury on the journey, because the clock regained its former rate on the return to Paris; and thought being put upon the right track, the effect was traced to its cause (Ref. 30). The small variations in $g$ are now accurately measured as part of the regular work of the Geodetic Survey, and of the scientific observations connected with polar expeditions, etc.

**174.** It is obvious that the beat of a pendulum which is caused to swing by its weight will be quicker, other things equal, for greater values of $g$; that is, for stronger pull of the earth, urging it toward its lowest position. And it is easily seen that such a pendulum favors the observation of minute variations in weight by accumulating them. Since there are 86,400 seconds in a day, an imperceptible difference in the time of one swing is magnified in a large ratio by keeping the pendulum under observation for a few

days. With the simplified form of pendulum consisting of a small leaden or iron ball hung by a thread, we may verify roughly by actual trial the relation (approximately true, but sufficiently accurate for many purposes) among the time of beat ($T$), the distance from the point of support to the centre of the ball ($L$), and $g$ (Ex. 101): —

$$T = \pi\sqrt{\frac{L}{g}}. \tag{29}$$

The main element in weight is the attraction of all substances for each other which was inferred and stated by Sir Isaac Newton, and is designated as **gravitation** (Ref. 31). Like all other bodies that we know, the earth and everything round it seem to be pulling toward each other. The result of gravitation grows weaker as we go farther away from the earth's centre; indeed, comparing this effect of the earth upon bodies near its surface with that upon the moon led Newton to discover his rule about the magnitude of these attractions. Assuming a body to be above the earth's surface at a given distance from its centre, the force of attraction is divided by 4 if that distance be multiplied by 2, the force is divided by 9 if the distance be multiplied by 3, and so forth. The square of the distance when multiplied by the corresponding force gives a constant product; or the ratio of two forces is the inverse ratio of the distances squared. Put this in symbols, $F$ and $F_1$ being two values of the attraction, $D$ and $D_1$ the corresponding distances of the body from the earth's centre. Then

$$FD^2 = F_1D_1^2; \quad \frac{F_1}{F} = \left(\frac{D}{D_1}\right)^2. \tag{30}$$

This is the famous "Law of inverse square."

After the fact has been detected, the way is smoothed to realize why we ought not to expect the intensity of the earth's influence upon bodies near its surface to be exactly the same everywhere: (1) the earth is not perfectly spherical, but "flattened at the poles," and therefore points on its surface are unequally distant from its centre; (2) the earth is not homogeneous in material, and the local differences in its crust affect weight; (3) the earth is turning on its polar axis once in twenty-four hours, the consequence being that gravitation at any place is active in other ways than in adding to the speed of falling bodies, and that the value of $g$ is smallest at the equator, where the other demands upon gravitation are greatest.

## INERTIA

**175.** We shall now undertake to complete the statement made in § 173, where it was pointed out that two elements enter into the magnitude of weight, by considering somewhat further the one that we are to associate with the heavy body itself, rather than with the earth. In the first place, appealing to universal experience, it is known that bodies differ widely in regard to the ease with which they can be set in motion and stopped. To kick or to catch a football in its normal state is quite another matter from making an attempt at the same ball if it is filled with sand. Chaff can be winnowed from grain by a current of air that scarcely stirs the latter. It requires greater effort to start a loaded freight-car than an empty one, on a level track.

In many examples like these, that will occur to everybody, the difficulty referred to is distinctly different from

that caused by an opposing force like friction, or by weight when we lift objects. It remains after friction has been made small by devices such as "ball-bearings," and where the influence of weight has been removed by balancing it, or by confining the motion to a horizontal plane (Ex. 102). The term **inertia** has been given a special meaning, and connected with the behavior peculiar to bodies in this respect; they are said to show greater inertia in proportion as it is more difficult to set them in motion.

Having attached a rough idea of "greater and less" to inertia, the next step is to decide upon some definite plan of measurement for it, as we have done previously for weight, pressure, quantity of heat, work. And this brings us to the choice of a standard, by comparison with which the inertia of bodies may be expressed numerically. Suppose that two Weights (see § 22, foot-note) are let fall together from rest at the same place, and that one is marked 100 grams, the other 500 grams. If the conditions are sensibly like those of falling in a vacuum, the Weights will remain side by side during the descent, each being "set in motion" just as fast as the other. But, though the speeds are equal after falling for 1, 2, or 3 seconds — or any number — they are not brought about in the two Weights with equal ease; the motion is executed under a continual pull of 100 gr.-wt. in the one case, under a pull of 500 gr.-wt. in the second. The pulls being constantly in the ratio of 1 to 5, and the motions being identical to the eye, the reasonable suggestion from the facts is that it is just five times as difficult to get the second Weight under way as it is the first; or the inertia of the body marked 500 grams is five times that of the one marked 100 grams.

Further trial proves that such a comparison of inertias by means of weight gives results that are applicable everywhere, and under all conditions. However these two Weights, for instance, are caused to run through any series of identical values for speed in the same line, the forces exerted by springs, muscles, magnets, etc., and pulling the Weights along the line, are always in the same ratio of 1 to 5; their comparative inertia is the same in all circumstances. Bodies can be changed in color, texture, volume, temperature, physical state, or magnetic properties by many processes; and in weight by actual shifting of position on the earth. But they become neither more nor less easy to set in motion or stop, whatever changes in their properties occur otherwise; their inertia remains constant, so far as our experience extends.

## MASS

**176.** When the Weights compared represent the same number of grams, their inertia is equal; and this consideration adds a new use for the standards called Weights, and for the operation of weighing on a balance with equal arms. The Weights are adopted as standards of inertia, the unit being one gram; and weighing an object enables us to read off its inertia on adding together the number of grams represented by the standards that counterpoise it. The steps by which the plan of measuring inertia grows out of the observed fact that the balance swings evenly should be clearly apprehended; the two important thoughts are: —

(1) Because the beam is balanced, the pull of the weight on each side of the knife-edge is equal.

(2) Therefore the objects weighed, and the standard Weights that balance them, would fall (in a vacuum) keeping side by side under the influence of equally strong pulls. Consequently they have equal inertia, whose value is read from the standards.

When inertia is measured in this way it is called **mass**; a body of great inertia is then appropriately spoken of as "massive." The mass of a body is constant (provided that no material be added or subtracted), although its weight alters slightly with its position on the earth. Mass is the factor contributed to weight by the quality of the body itself; objects are heavy in proportion as they are massive, and also in proportion as $g$ grows larger in value. Notice particularly that the word "gram" must be kept as the name of the unit when we measure mass, while "gram-weight" is reserved for the unit in terms of which weight and other forces are measured. Our Weights have a double service to render: (1) in themselves they are standards of mass (inertia); (2) through the pull of the earth upon them they become standards of force.

To say that an object has a mass of 365 grams would mean that its inertia is equal to that of the group of standards $(200+100+50+10+5)$ grams. If you reduced this to English measure, should it be expressed as pounds-weight, or as pounds?

Would you expect the same objects to remain counterpoised by the same standard Weights on equal-arm balances at different localities?

In using a spring-balance, are you dealing with mass or with weight (*i.e.* with inertia or force) more prominently?

## DENSITY

**177.** In problems concerning homogeneous substances, it is often convenient to know the mass corresponding to 1 c.c., as a starting-point for calculating the mass of other volumes. Thus, if 1 c.c. of brass is found to have a mass equal to that of 8.5 grams, the mass of a brass block 10 cm. long, 15 cm. wide, and 6 cm. high would be $((10 \times 15 \times 6) \times 8.5)$ grams (Ex. 103). The mass reckoned for 1 c.c. is called the **density** of the material; it can be obtained as the quotient of the measured mass of a body by its measured volume. If $D$ denotes density, $M$ mass, and $V$ volume,

$$D = \frac{M}{V};\quad DV = M. \tag{31}$$

If the density of a substance $S$ is $D$, and that of a substance $S_1$ is $D_1$, show that the specific weight of $S_1$ referred to $S$ as a standard is $\frac{D_1}{D}$ (see § 26).

What would you understand by the phrase, "average density of a body" (see § 27 (1))?

Are specific weights expressed according to English measures different from those obtained when metric measures are used?

When the volume of a body is given in cubic inches, and its mass in pounds, what value has the density of water? of iron? [1 cu. in. = 16.39 c.c.; 1 pound = 0.4536 kg.]

Does the idea of density require comparison with a standard substance like water? Why are the numbers for the density and the specific weight of a substance almost identical when the metric system is employed (see § 100, table)?

Since the weight ($W$) of a body depends, as we have seen in § 176, partly upon the mass ($M$) and partly upon the locality (introducing $g$), it is proportional to both $M$ and $g$, or to their product $Mg$, and we can write in symbols $W = CMg$, $C$ being merely a constant factor indicating the proportionality. Hence it follows that $\frac{W}{g} = CM$, showing the quotient $\frac{W}{g}$ to be proportional to the *mass*, and therefore not dependent upon the locality. Consequently, the expression for kinetic energy, $\frac{Wv^2}{2g}$, can be put into the form $CM\frac{v^2}{2}$, which brings out once more the fact that energy in this form depends upon nothing but the body itself (through its inertia) and how fast it is going (see § 170). It is instructive to note how the ideas of inertia and energy are linked together here. The more difficult a body is to stop (*i.e.* the greater its inertia, or $M$), the more work it can do before it stops (*i.e.* the greater its kinetic energy), the speed being the same.

On the other hand, potential energy ($Wh$) for a given difference of level ($h$) depends upon the locality, because the weight ($W$) varies from place to place.

# CHAPTER XI

## SOUND

**178.** When the nerves of our skin are made to sting in the neighborhood of hot bodies, or by contact with them, we call the sensation heat. In the study of Physics, however, the conditions prevailing among the objects which cause that sensation occupy us more than the sensation itself does, and we have learned to use "heat" with a different meaning, as the name for a physical quantity. Similarly, a special sensation in our ears, and a peculiar state within surrounding bodies which gives rise to the sensation, are both spoken of as sound. Here, too, we shall use the word exclusively in the latter way, because we are not concerned with ourselves so much as we are with sources of sound, its transmission, and in general what happens before the sound reaches us.

We recognize as sound, at once, all musical notes or noises that can be heard; and, having traced such influences to their cause in "sounding bodies," these are **sources of sound** for us. Steam-whistles, bells, piano-strings, organ-pipes, the throats of men and animals, a waterfall, wagons rattling over the pavement: the list of familiar examples like these could be prolonged indefinitely. In many instances it can be observed directly that an object becomes a source of sound after merely being struck, or otherwise disturbed mechanically, as an

anvil rings under the blows of a hammer, and the strings of a guitar give their notes when plucked. It can be felt, too, that the state of sounding bodies themselves is one of mechanical disturbance and motion, — if we touch them; and it is often seen that they cause loose objects near them to rattle and shake.

These facts, which are matters of common observation, justify us in ranking sound as a result of work, and in connecting it closely, at least, with kinetic energy. If a tuning-fork, which has been made a source of sound by striking it, is held freely in the air, after a little while it ceases to sound; the energy that rendered it a source of sound has left it. Now it has been seen that a heated body in circumstances like those of the tuning-fork may part with its heat-energy in three ways: (1) to a solid support by conduction; (2) to the air, which carries off heat by means of convection currents; (3) in the form of radiation. What are we to think about the diminution of sound-energy in the fork; is it due to processes like all these, or any of them?

## SOUND AS RADIANT ENERGY

**179.** Before attacking the question directly by experiment, it is worth while to notice that sound is given off in all directions round the fork, as judged by our hearing its note, wherever we place ourselves near it. This suggests that something akin to radiation is sent out, and makes it desirable to follow up the comparison. The remarkable property of radiation, in our previous experience of it, is its power to traverse a vacuum. Sound fails to meet this test (Ex. 104); it seems, then, to be radiated *by means of*

air, as well as through it. With this understanding, there is no contradiction in applying the name "radiation" to sound or other influences that are handed on along the radii of spheres described about the active centres. For sound, these centres are the effective parts of the sounding body.

Let us examine further, before we accept it, the proposal to regard sound as a particular form of radiant energy in its passage through air and other substances. Like radiation that we have encountered before, sound can be reflected; it is also transmitted in some circumstances, absorbed in others (see § 154). The sound of voices or footsteps comes back to us after reflection at the walls of an unfurnished room; the echoes out-of-doors from cliffs and the walls of buildings, which are part of everybody's experience, yield additional evidence of reflection, and the "rumbling" of thunder is observably due to the same cause. The accumulation of sound-energy at one place by reflection from curved surfaces makes sounds audible that would not be noticed otherwise; this consequence is exhibited in so-called "whispering galleries," where persons at special positions can converse in whispers, though their distance apart would render that impossible in an unenclosed space. The effectiveness of speaking-tubes in houses, of ear-trumpets for the deaf, and similar devices depends upon guiding the energy in narrowly limited channels, by reflection from their walls, instead of allowing it to radiate freely in all directions. When that freedom is permitted, sound is heard more faintly as we go farther away from its source. This effect of increasing distance is exhibited by all forms of radiant energy, and follows naturally from

distributing the supply over the surfaces of larger spheres, in going outward from the active centre; the share falling upon an area of given size, like the opening of the ear, becomes rapidly less.

As regards transmission and absorption, we know that sound is "deadened" by being received on materials that are soft and yielding, like the draperies and hangings of a room, and that drums are "muffled" by the use of similar textures. But wooden partitions and ceilings transmit sound so readily when it has once entered them (though they reflect it strongly, too, as it enters from air), that it becomes necessary to employ "deafening" of some kind, where it is desired to avoid these results. Substances that ring and are sonorous transmit sound well. Putting together the items thus far enumerated, there are features enough of essential resemblance between other radiation and sound to justify the description of the latter as radiant energy, answering query (3) in § 178.

## SPEED OF SOUND

**180.** The senses of sight and hearing often give us two impressions connected with the same phenomena. We see an axe or hammer brought down, or the partially condensed steam issuing from a whistle, and hear the corresponding noise. But the sound reaches us perceptibly later than the moment when the eye tells us that the whistle is set in operation; and we see the blow struck before we hear it. In all such cases, the sound appears to lag behind the radiation called light, when both come from what is practically the same source. Direct experiment proves that this delay is due to the comparatively

slow speed of sound through air, and not to a difference between eye and ear in the time required to become aware of the sensation. The continuance of sound after it is seen that steam has been shut off from a whistle is, of course, explainable on the same basis. We hear until the supply of radiation in the air between us and the source, which has therefore already started on its way to us, is received (Ex. 105). The speed of sound in air is influenced somewhat by the temperature at the time; it is not far from $34 \times 10^3$ centimeters a second for 15°. Sound travels faster in water, wood, iron, and glass, than it does in air; the speed is from 4 to 20 times as great (Ex. 106).

A tuning-fork that is sounding can be heard more plainly when its stem rests against a table, than if held in the hand, or suspended in the air; and, as might be expected, it also becomes silent sooner by exhausting its sound-energy more quickly (Ex.). At first sight, this may look like a parallel to the more rapid cooling of hot water in a vessel placed on a plate of cold copper, and losing heat by conduction. But the high speed with which sound travels in wood should make us pause before adopting that conclusion. The carrying of heat by conduction is a slow process of seeping, in comparison with this speed of several hundred meters a second. It should be said that the manner in which sound is conveyed by wood turns out, on fuller examination, to be just like that in air (see query (1), § 178). A table against which a tuning-fork is held acts as a "sounding-board" does in violins and other musical instruments. It enlarges the surface of contact at which sound can enter the air, with the result that a larger quantity of sound-energy reaches the ear in a given time by means of the air.

We shall not raise any question about possible transformation of sound into other forms of energy, nor discuss more particularly the nature of sound-energy itself. Convection currents of sound (*i.e.* sound conveyed by a stream of air) are not observed (Ex. 107).

## LOUDNESS AND PITCH

**181.** Other circumstances being alike, the **loudness** of sound from a given source grows with the vigor of the mechanical disturbance caused and maintained there. In order to produce louder sound, a gong or drum is beaten more violently, piano-keys are struck harder, air is admitted to organ-pipes more freely from the wind chest, and so forth, in numerous examples that lie ready to hand in our experience. But there is a second element of sounds—called **pitch**. Soprano voices of women are high, the voice of a bass singer is low, and distinctions like this are recognizable among musical instruments, or other sources of sound. If loudness is determined by the supply of energy, in what do these differences of pitch among sounds consist?

We shall be helped toward the answer to this question by examining more closely the general character of the disturbance at a source of sound. And it is not difficult to show, in some cases at any rate, that the conditions at a source are unsteady; that is, fluctuating or intermittent. With the contrivance known as a siren, the intermittence is secured mechanically, and in such a way that a jet of air passes through the revolving plate and is stopped by it, alternately, the number of times that this happens in a second being under control (Ex. 108). A note is thus

produced, whose pitch rises as the alternation between starting the jet and stopping it is made more rapid. The siren proves only that it is *possible* to sound a note in this fashion; we need to know whether the same evidence is repeated where the conditions at the source of sound are self-regulated, and not imposed by a mechanical device. A gas-flame that "sings" of its own accord within its glass chimney supports fully the conclusions drawn from the previous trial; the fluctuations are a marked feature, and a greater rapidity in them corresponds to the note of higher pitch (Ex. 109).

Further experimental analysis of the conditions at sources of sound leads us to look upon rapidly repeated changes of some kind as indispensable to their activity. Every quick variation of pressure in portions of gas, or of position in taut strings, or of length and bulk in rods, disturbs the air around them, moving it suddenly, and changing its pressure locally as they crowd it out of their way, or allowing it to expand when they retreat before it. Part of the energy added to the air by the work during such disturbances is carried as radiation to our ears. A repetition of the disturbance at equal intervals of time is necessary to the production of a musical note, whose high or low pitch is found to depend upon nothing but the number of repetitions that occur and reach the ear in one second; this number is called the **frequency** of the note. The confused impression caused by an irregular series of changes is heard as a noise.

Our ears do not respond to every influence that can prove its right to be classed as a sound in the physical sense. The air may repeat regularly at our ear-drums changes of the proper character, but we are deaf to them

if their pitch is higher or lower than a certain limit. This is well established as a fact, but the limits cannot be set very definitely. We may say roughly, however, that audible sounds have frequencies above 30 (complete series of changes) a second, and below 10,000 a second. In studying phenomena connected with notes of very high pitch, the sounds are detected by other effects than those upon our ears (Ref. 32).

## QUALITY OF SOUND

**182.** The sounds that we usually hear cannot be described adequately in terms of their loudness and pitch alone. Everybody is aware that the voices of men, the cries of animals, and the notes of musical instruments have characters of their own by which they can be distinguished and identified, even where the conditions for giving notes of the same pitch are fulfilled as accurately as possible. Characteristics of this sort add to the note what is called its **quality**. Without going beyond our depth in difficulties, it can be understood as a leading idea, that the particular quality of a sound is due to a modification of its principal constituent by which the pitch is assigned. The special modes of producing and sustaining sounds with rosined bow, or larynx, or mouthpiece, register their consequences in minor and subordinate regularities blended with those of larger scale, and bearing to them a relation like that of a ripple-marking to the ocean swell on which the wind traces it, or the series of temperature changes within twenty-four hours, that is repeated many times in running through the seasons, to the slow rise and fall of the daily average once in the year. The eye distin-

guishes between carpet-patterns though they are alike in their larger blocks, if they are varied in the details; and the impression of an actual sound upon the ear includes not only the spacing of the main intervals (pitch), but also the way in which they are filled out (quality). This thought is connected intimately with the perception of difference, other than that in loudness, between concerted music and performance upon a single instrument.

Neither the pitch nor the quality of a sound appears to affect its speed in any given substance. What effects would be produced on listening to orchestral music, if the speed of a sound varied noticeably with its loudness, pitch, or quality?

## MUSICAL INTERVALS

**183.** In order that notes should cause an agreeable sensation when heard in association, and especially if they are sounded together as a chord, their frequencies must bear certain ratios to each other; and the notes of our musical scale are so selected as to recognize that necessity. What is called an **interval** between notes in music depends upon the ratio in which one frequency stands to the other, and not upon the difference between them. The scale is divided first into octaves, in which the highest note has twice the frequency of the lowest, and then subdivided. The extreme note of one octave being made the starting-point for the next, the subdivisions are repeated in as many octaves as the scale includes. Going up the major chord, the relative frequency of the four notes is represented by the numbers: —

| | | | |
|---|---|---|---|
| C | E | G | C |
| 4 | 5 | 6 | 8 |

Hence the interval C — E, called a "major third," is measured by the ratio $\frac{5}{4}$; the interval C — G, called a "fifth," corresponds to the ratio $\frac{3}{2}$. The striking fact here is the smallness of the numbers by which the ratios in their lowest terms are expressed. The intervals named are generally felt to be most satisfying to the ear; and discord is approached (within the octave) as the interval becomes expressible in larger numbers only. For example, no pleasant impression would result from two notes sounded together, if the ratio of their frequencies were $\frac{19}{21}$.

The frequency chosen for the first note of an octave, which assigns to the scale what is called "absolute pitch," plays no part in making the chords agreeable. But as a matter of convenient international understanding, the A above the middle C of the piano key-board, usually written a′, has a frequency set at 435. According to that standard, when a′ is sounded on a tuning-fork, its prongs execute 435 complete movements (approach *and* recede 435 times) in one second.

## RESONANCE

**184.** Stretched strings and other solid bodies, or limited portions of gas in tubes, are often susceptible in a marked degree to sounds of a particular frequency, which they respond to by accumulating the energy received, until they become sources of sound themselves. One common method of exhibiting this fact is to sound a note (by singing or otherwise) near a piano after raising the cover, and lifting the dampers from the strings with the "loud pedal."

What strings do you find especially strong in response to the note sounded?

Or a column of air (and water-vapor), contained in a wide tube open at the upper end, and varied in length by a "movable piston" of water, can be adjusted to "reënforce" the note of a given tuning-fork held over the opening (Ex. 110). These phenomena are known as **resonance.** The body in which the sound-energy is thus accumulated becomes a **resonator** for sounds of that frequency. The response is much weakened by departing from the position of adjustment, or by substituting a tuning-fork giving another note.

After obtaining the position of strongest resonance in the above experiment, remove the fork, and make the air column a source of sound by blowing across the mouth of the tube. How does the sound now heard compare in pitch with the note of the fork?

If two tuning-forks that have accurately the same frequency are selected, and one is made to sound its note by striking it, the other can be excited at a distance of half a meter, under favorable conditions, purely as an effect of resonance, the energy being conveyed by the air between them (Ex. 111). Other observed instances where objects "pick up" a note sounded near them are in line with these experiments. In rare cases sufficient energy to shatter it can be accumulated by a glass vessel under the influence of a strong voice singing close to it; and it is common to find smaller articles in a room especially sensitive to particular notes of a piano. These consequences are regularly developed most strongly, when the object as a source of sound emits a note of the same pitch as that for which it is a resonator.

**185.** The tube of Experiment 110 being adjusted to greatest resonance with a second tuning-fork of different pitch, the new length of air column found is greater if the second pitch is lower, and shorter if the pitch is now higher (Ex. 112).

The comparative length of organ-pipes giving high and low notes is well known. Does your observation of such pipes as sources of sound, in connection with the present experiment, strengthen or contradict the supposition that resonators are effective for notes of the same pitch as those which they emit when used to produce sound?

Any one of the adjustments between tuning-fork and resonance-tube is disturbed if coal-gas be substituted for air (Ex. 113). If now strong resonance to the fork be reëstablished with an atmosphere of coal-gas in the tube, are the columns longer, or shorter, than the corresponding columns of air? Which is specifically lighter under the equal pressure during these experiments, coal-gas or air? [Water-vapor is present with both gases.]

In the circumstances considered up to this point, the energy is delivered to the resonators as sound and simply accumulated by them. But they can become sources of sound under other conditions, when supplied with what appears to be ordinary mechanical energy, often in the kinetic form. Whatever transformation may be necessary (if indeed any is needed) is then provided for in the resonator itself. Bells are just struck with a hammer, but they emit definite notes. There seems to be no regularity of alternation in the friction of a wetted finger on the rim of a tumbler, nor in that of a rosined bow on a violin string; but a clear musical note results in both cases. The chimney being slipped over the flame in Experiment

109, a sustained note is gathered out of the irregularities in draft through the tube; and an organ-pipe is blown with an apparently steady blast of air.

It is worth while to examine these circumstances attentively, in order to appreciate the situation that confronts us here. The first light upon what is obscure in tracing the consequences from the conditions is afforded by three considerations, as follows: —

(1) A perfectly steady force, or a completely uniform flow, is not met with in our observations of phenomena. Wherever processes ordinarily called steady or uniform are closely scanned, and measured with precision, minute irregularities are discoverable.

(2) Very small forces, *if properly timed*, may accumulate consequences of unexpected magnitude. For example, hang a heavy ball by a wire, and note the time of its free swing as a pendulum. Attach a thread to it, and, while it hangs at rest, pull slightly in a horizontal direction, and repeat the pull at intervals equal to *twice* the time of swing from left to right. The force will then be applied at each repetition, as the ball passes in the same direction through its lowest position. With care in timing the pull, a swing through a considerable arc can be produced by a force that gives no visible result at first.

(3) Under perfectly steady pressure, the air column in a pipe would settle down to constant volume; a stretched string would be pulled aside to a new permanent position if the grip of friction were perfectly uniform. But even the smallest irregularities of air pressure in the blast, or of frictional contact with the bow, must be met continually by alterations of volume in the air column, changes of form in the string. The very word "irregularities"

implies the absence of *rule* in the original timing of such disturbances; but, just because they happen at random, some will be timed to the frequency determined by the material, size, and other conditions of the resonator. That there is such a "natural" frequency our experiments have proved. The action of the resonator is now twofold: first, it selects such opportunities to increase its own energy as are offered at favorable instants; and secondly, by gathering energy it becomes more powerful in impressing its own rhythm upon the phenomena, thus adding to the number of chances that are properly timed.

These statements describe the facts thus far, and should prove helpful toward the further study of them. But we must not claim that adopting this point of view brushes away the difficulties; it only puts into our hands clews to be followed.

## NOTES OF STRINGS

**186.** A stretched string or wire is made to sound, if pulled aside from its undisturbed position and released. When the notes given under such circumstances are observed, three elements are found to influence their pitch: (1) tension, or the magnitude of the force by which the stretching is done; (2) material; (3) length, or distance between the fixed points at which the wires or strings are held (Ex. 114). We shall attempt to state the general reasons why pitch or frequency is affected by these conditions, and show what kind of changes must be made in order to produce a given alteration of the note.

While returning to the original position, the parts of a wire are set in motion; the greater their inertia, the more slowly they will start under a given pull, and the longer

it will take to move back over a given displacement. Other things being equal, therefore, the material having more mass will sound the lower note. But with given mass and length, the "snap back" will be quicker the stronger the pull; so increase of tension raises the pitch, if the other elements remain unchanged. Though the disturbance is caused at one place, it spreads along the whole length finally, and the recoil must include the whole wire, the effects being handed on at a definite speed from one part to another. Consequently, the time required to draw the full extent of the wire into the plan of motion will increase with the distance apart of the fixed ends; or the frequency of the complete cycle of motions is less when that distance is longer.

What examples can you give of stringed instruments in which pitch is raised by tightening the strings? Name some instances where shorter strings are used for higher notes. What effect does the "fingering" of the violin and guitar have? What object is attained by loading some strings of the piano with wire that is wound on them in tight coils?

Which of our observed results in resonance-tubes show the influence of material and length there to be like their influence upon the note of a string? What quantity that applies to a column of air would correspond to the tension of a string? Why does rise in temperature change the note of an organ-pipe? If the barometer height varies, and temperature does not, the specific weight of a gas is altered. Should change in barometer height alone, then, affect the pitch of an organ-pipe?

Some additional matters are suggested in Reference 33.

# LIGHT

## CHAPTER XII

### SOURCES OF LIGHT. ILLUMINATION AND SHADOWS

**187.** The remark made about the double meaning of heat and sound at the beginning of Chapter XI may be repeated with regard to light. A special sensation of light is excited in us through our eyes, that renders us aware of qualities like color, outline, and brightness in the objects around us. And in the other use of it, light is the agency or influence by means of which such impressions are conveyed to us from those objects. The latter meaning is the one more particularly connected with the general purposes of Physics, and we shall employ the word in that sense. It has been pointed out previously that light, like heat and sound, is one form that energy assumes during its transformations (see § 140, § 154).

#### SOURCES OF LIGHT

As there are sources of heat, sources of sound, so we speak about sources of light. It may be said that everything visible is such a source for us; and we can agree to the truth of that statement, if it be understood at the same time that we recognize a division of sources of light into two groups. The first comprises those objects which are visible independently, like the sun or an arc-lamp; more

specifically, we call these **luminous**. The second group are visible only with the aid of some source that is itself luminous; they are then **illuminated**. Thus, the walls and furniture in a dark room are invisible, but they can be seen if a lamp is lighted there; moonlight is sunlight at second-hand. It can be assumed as generally known that illuminated surfaces become visible by reflecting some of the light which they receive from luminous sources. This account of the matter is sufficient for the present; it is supplemented to the necessary extent in the chapter on reflection.

**188**. The luminous sources of "artificial light" in ordinary use consist of solids that have become incandescent at a high temperature. This is seen directly in the incandescent gas-burners and electric lamps; the effective part of the arc-lamp is the white-hot carbon, and the source in the "calcium light" is a piece of lime, made white-hot by an oxy-hydrogen flame or its equivalent. The light of "flash powders," used in taking photographs at night, comes from heated particles of solid magnesium oxide; and the flames of hydrocarbons like coal-gas, acetylene, kerosene or other oils, and candles, are luminous by virtue of solid carbon separated in the act of burning. When air is mixed with the gas in such a way that the solid carbon does not appear in the flame, the latter becomes nearly non-luminous, although much hotter (gas-stoves, Bunsen burner, etc.).

Some chemical compounds used in "luminous paints," and a few insects like the firefly are exceptions to the rule of high temperature at these sources of light. They belong to the group of phosphorescent substances about which something more is to be said later.

## ILLUMINATION

**189.** Every small subdivision of a luminous surface is a centre from which light is radiated to a distance through air; so that what we are in the habit of describing as one source is really an assemblage of sources, each of which is sending light outward in every possible direction. Taking a centre at any particular part of the surface, the light fills up something like a hemisphere around that centre. The diagram (Fig. 59) represents such a small area at $A$, and a section of the corresponding hemisphere by $BCD$; below $BD$ light cannot issue, being cut off by other parts of the source.

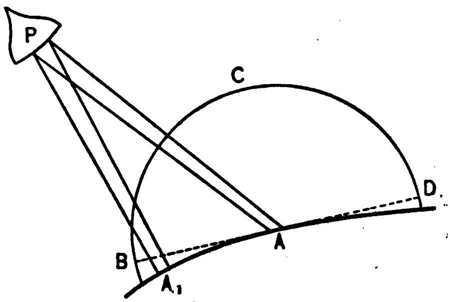

FIG. 59.

We see objects in air by means of light that is received from them upon the pupils of our eyes, which are round openings from 0.2 to 0.5 cm. in diameter; they adjust themselves within certain limits, according to the brightness of the light, and their size is not the same in all persons. The pupil of an eye is shown at $P$, and the straight lines diverging as they go from $A$ to $P$ indicate the boundaries of the light by which $A$ is seen in these circumstances. The smaller $A$ is taken, the more nearly we have a cone of light, with its vertex at $A$ and its base at the pupil of the eye. A similar cone belongs to any other part of the source, like $A_1$, and all such cones have a

common base at $P$. The effective light admitted to the eye will traverse the space marked out by the entire closely fitted group of these cones, to which each small area in the source contributes one. If the light comes from a disk of considerable extent (Fig. 60), and the area of the pupil is small by comparison, the group of cones will merge into a conical volume with its vertex at the pupil and its base at the luminous disk. And in any case the light received at the eye will fall within a sort of conical volume with its vertex at $P$, but the base will follow the outline of the source as seen from that point; the diagram (Fig. 61) represents these conditions for a gas-flame. The same relations exist if $P$ is not the pupil of the eye, but a point in any object upon which light falls. This aggregate of light received at any point determines what is called the **illumination** there due to the source.

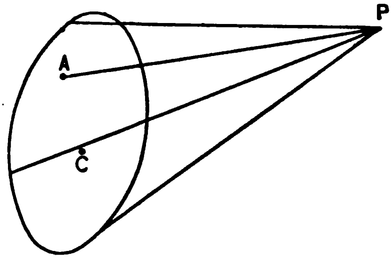


FIG. 60.

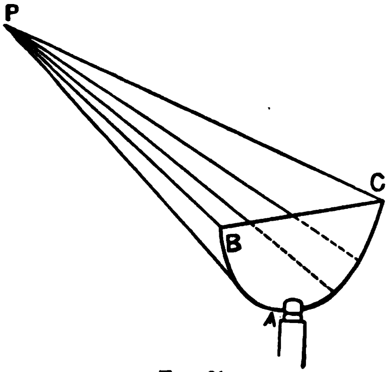


FIG. 61.

**190.** It has been remarked before, in speaking of sound as well as sunshine, that radiation can be reflected, trans-

mitted, or absorbed by different substances placed in its track (see § 154, § 179). Air and other gases, clear water, glass, and crystals like quartz and the diamond, are examples of materials through which light is allowed to pass with a good degree of freedom; they are said to be **transparent**. Some materials, like cardboard, wood, brick, and metals, hinder completely the passage of light, and are termed **opaque**; mirrors reflect light. The details of these phenomena are to engage our attention successively as we proceed; and we make a beginning by speaking of some effects produced upon illumination, if an opaque substance is interposed between a luminous source and the points upon which its light would otherwise fall.

The cone represented in Fig. 60, which we shall call the **cone of illumination**, may be taken as showing an eye at $P$ in relation to any circular luminous surface. If the perpendicular distance, $PA$, of the eye from the source is not so great that the opening of the pupil can be regarded as a point in comparison with it, the eye can be thought of as looking through a smaller opening still, like a hole in a card; or we can refer to $P$ more definitely as the centre of the pupil. Considering the sun's disk as the source, the point at the foot of the perpendicular will fall at the centre $C$, and the eye can be taken as a point on the scale of lengths such as the sun's diameter and its distance from us. But immense as the size of the sun is, its direct light can be cut off from the eye with any opaque object whose outer edge lies on the surface of the cone of illumination. Thus a silver dollar held at arm's length can be made just to "cover" the sun's disk. The moon fulfils that condition for some points on the earth, when a total eclipse of the sun occurs. At a greater distance from the

eye, the face of the dollar is not so large as the cross-section of the cone, and part of the illumination reaches $P$. Holding the centre of the dollar on the axis of the cone, and its face perpendicular to that axis, a *ring* of light then appears beyond its edge, and the conditions of *annular* eclipses are reproduced. Ordinary partial eclipses of the sun correspond to moving the dollar a little to one side.

These familiar illustrations emphasize two thoughts: —

(1) That all the light reaching a given point from a luminous source is contained within the cone of illumination. We shall extend the latter term to cone-like volumes such as $PBAC$ (Fig. 61), through which illumination passes to $P$ from any source $BAC$.

(2) That what is called *angular* size counts here, and not linear dimensions. All cross-sections of a cone have equal angular size as seen from its vertex, because any one just covers those behind it, when projected upon them as a background. The diagram (Fig. 62) shows angular size measured in a plane. Let $P$ be the eye, $AB$ the line in which the front surface of an object is intersected by the plane of the paper. Then the angle $APB$ measures the angular size in the direction $AB$. If $AB$ is a diameter of the sun, the angle $APB$ is about 32 minutes as seen from the earth; the angular size of the sun is 32 minutes, and if $CD$ fits in the angle, it will cover the sun on that line, as seen from $P$.

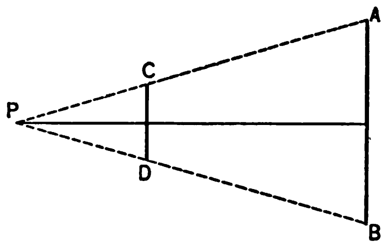


FIG. 62.

## SHADOWS

**191.** When an opaque body, that we shall term a screen for brevity, is introduced into the cone of illumination for any point $P$, part or all of the light being cut off from that point, it is said to be in the shadow of the screen. Two regions are commonly distinguishable in such a shadow. The first includes all points from which illumination is cut off entirely; this is known as the total shadow or **umbra.** The points in the partial shadow or **penumbra** still receive some illumination, but not so much as though the screen were removed. From the ideas already connected with the cone of illumination, it follows that no part of the source is visible from points in the umbra, while some portions of it can be seen from points situated in the penumbra.

The sun, moon, and earth being spherical, the umbra and penumbra in shadows cast by the last two when the sun is the source are easily located. The diagram (Fig. 63) exhibits the relations in any one plane through the centres of the sun $S$, and the earth $E$,—everything being symmetrical about the line joining those

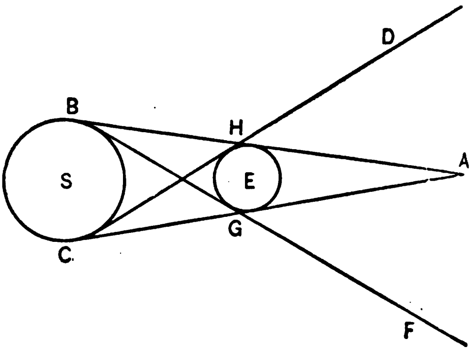


Fig. 63.

tres. $BA$ and $CA$ are externally tangent to both s; $BF$ and $CD$ are the "crossed" tangents. Show

that no part of the sun's disk would be visible from the region *GAH*. Choose a point somewhere in the region *AHD* or *AGF*, and determine what portions of the sun could be seen from it. What are the boundaries of umbra and penumbra in this case? How would the conditions be changed if earth and sun were of the same size? If the earth were larger that the sun?

Show that the region of partial shadow shrinks when the angular size of the source, as seen from the screen, becomes smaller. How does a comparison of sun shadows and electric-arc shadows illustrate this conclusion?

## ILLUMINATION THROUGH OPENINGS

**192.** The cone of illumination may be obstructed in a somewhat different way, if a large screen has in it an opening of smaller area than the section at that place of the cone of illumination. The diagram (Fig. 64) represents those conditions for a gas-flame *F*, a vertical screen *S*, and a point *P*. The full cross-section of the

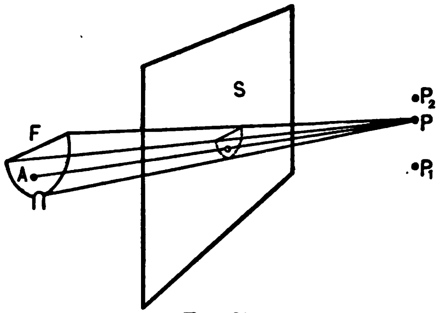


FIG. 64.

cone at the screen is shown as a dotted semicircle, while the actual opening is the smaller circle within. With the dimensions indicated in the figure, it is evident that the effective illumination at *P* would come from the limited area of the flame near *A*; but the top only of the flar

would send light to $P_1$, and its lower part to $P_2$. If the light from $F$ were received through this small opening upon a white wall at $P$, parallel to the screen, each small area of the flame would illuminate one particular small area of the wall, and show there the peculiarities of its own light. Consequently, an *inverted picture* of $F$ is formed when these conditions are realized (Ex. 115).

Why should the picture be increased in size if the wall were farther from the screen? What happens when the opening in the screen is enlarged, and why?

Suppose the dotted semicircle on the screen to be the opening. Why will there be no sharp boundary between light and darkness on the wall? Show that the partially lighted area is a penumbra.

Give some illustrations proving that the patch of light takes its shape from the sun when sunlight enters through a small opening, but from the opening itself when it is large. Explain these results.

What shape would you expect in the spot, when sunlight enters by a small opening during a partial eclipse?

**193**. Looking again at Fig. 64, it is evident that light radiated from all parts of the flame is mingled at the screen, in the opening where the tracks of the various portions cross. And, after passing through the opening, light spreads on the farther side of the screen, making a fresh start very much as though it was leaving a luminous source of small area, situated in the opening. Indeed, the fact being that a supply of light is furnished there, we can accept the opening in the screen as a source, and seldom need trouble to ask how the supply was obtained. On comparing this case with that of Fig. 59 (§ 189), however, one feature of difference becomes apparent and

should be noted. Whereas the light radiated from an element of area like *A*, in what we are inclined to term a real source, is distributed impartially throughout a hemisphere, the light is kept within a limited cone as it spreads from its new centre at the opening in the screen, the angles of such cones being determined by the angular size of the original source as seen from the new centre.

After sunlight has passed through small openings, its extreme portions in any plane containing the axis of the cone spread at an angle of 32 minutes, when the whole disk of the sun is taken as the source (see § 190, end). The diagram (Fig. 65) shows the relations in any such plane, *F* being now a diameter of the sun, and *S* the screen as before. A fixed star has no appreciable angular size for us, so the cones of light that we have been considering approach the form of small cylinders whose boundaries are parallel to each other. Light received from any small area of the sun is also an example of **parallel light**; but the illumination carried to a point by a "beam" of sunlight contains an assemblage of such cylinders, whose axes make all angles with each other, up to 32 minutes.

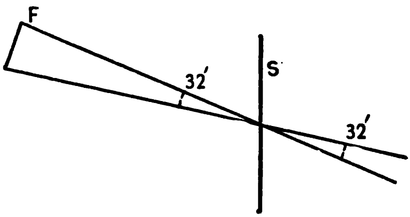

Fig. 65.

When light is admitted through two or more separate small openings in a screen, each one can be regarded as a source for the further effects of the light, according to the idea just presented. But one larger opening can always be subdivided into a number of smaller areas, to each of which the thought in the above form applies. And it is

often a helpful point of view to recognize such a group of what are practically sources in an opening near at hand, through which light enters, instead of referring to a remoter source like the sun. A device like this becomes especially useful in tracing the course of light within optical instruments like telescopes; and, in order to familiarize ourselves with it, let us consider sunlight in that way. Light from the sun falls from the right directly upon an opening in a vertical screen $SS$ (Fig. 66). Each pair of parallel lines drawn at any two points, $A$ and $B$, represents "parallel light" coming from the same part of the sun; if the dotted pair correspond to the lowest edge of the disk, and the other pair to the highest point, the angle between them will be 32 minutes. All such portions of parallel light cross in the opening, and proceed, diverging as they go, into the region to the left of the screen, for which $A$, $B$, and all other points of the opening, act like small luminous sources, sending out light of divergence limited to 32 minutes (Ex. 116).

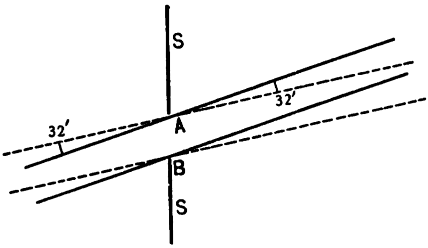

Fig. 66.

EFFECT OF DISTANCE UPON ILLUMINATION

**194**. As the supply of light proceeds outward from any part $A$ (Fig. 67) of a source, it is distributed over surfaces of increasing area, and its effect on each square centimeter is correspondingly weakened, like that of

sound (see § 179). Conditions are on a par in this respect at equal distances from $A$, provided that the light spreads evenly among all the directions along which it is visible. Consequently, the surfaces of equal effect are portions of spheres described around $A$ as centre. In comparing conditions at unequal distances from $A$, the leading thought is that the share of light obtained by 1 □ cm. varies inversely as the number of square centimeters among which the same total supply is divided. And, since the areas of corresponding parts like $S$ and $S_1$ (Fig. 67) on spherical surfaces of radii $R$ and $R_1$ are in the ratio of $R^2$ to $R_1^2$, the portion of light belonging to 1 □ cm. at $S_1$ is diminished in the ratio $\frac{R^2}{R_1^2}$, as compared with an equal area of $S$. This is again a "law of inverse square" (see § 174), which is met in so many cases of radiated distribution.

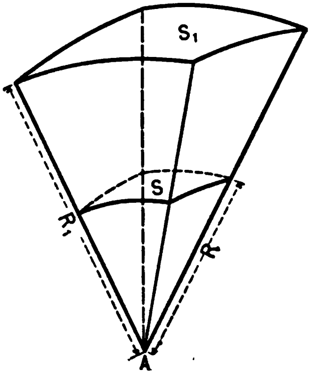

FIG. 67.

The supposition that the "same total supply" of light is available at the greater distance should be emphasized. If light is absorbed on its way from $S$ to $S_1$, its effects at the outer surface will be still further weakened.

The rule of inverse square cannot fit the circumstances, in dealing with the amount of light falling on 1 □ cm. from a source of considerable extent that is near to it, because there is no one centre like $A$ (Fig. 67) from which to measure, but parts of the source at different distances contribute to the supply of light for the same area. These

differences of distance disappear by comparison, however, when the area upon which the light falls is remote from the source, and the rule may then be applied. By realizing this condition experimentally, the relative supply of light sent to equal areas at equal distances by different sources like lamps and flames is often measured (Ex. 117). Instead of comparing the effects of two sources at equal distances, however, it is practically more accurate to adjust the distances of the sources from the equal areas illuminated by them, until equality of effect is produced. The rule is almost self-evident, that the strength or intensity of the sources is then directly as the squares of the distances at which they give equal illumination. Let the light supplied to 1 □ cm. at the same distance $D$ be denoted by $L$ and $L_1 (L > L_1)$. Then the distance $D_1$, to which the stronger source must be removed in order that its effect may be weakened to the value $L_1$ shown by the weaker source at a distance $D$, is given by the equation $L\frac{D^2}{D_1^2} = L_1$, or $\frac{L_1}{L} = \frac{D^2}{D_1^2}$, as the rule requires.

In measurements of this character, comparison of the light under test is made (directly or indirectly) with standard candles. The intensity of the source is then specified in terms of **candle-power**; we speak of a 16 or 32 candle-power electric glow-lamp. Express the meaning of such a statement more fully.

# CHAPTER XIII

## REFLECTION OF LIGHT

**195.** When light is passing through air and reaches the surface of water, or glass, or mercury, only part of it crosses the boundary to enter the second substance, even though that be transparent as water and glass are; another part of the light is turned back, or reflected, into the air. And we find, not only in these familiar instances, but more generally, that light is in part reflected when it meets the surface of any substance differing from the one in which it is. So far as results are concerned, reflection from surfaces like those of smooth water and mercury, or polished glass and metals, is commonly distinguished from the action of surfaces like rough water, ground glass, and dull or rough metals. It is said that we see images by reflection in the first case, and see the reflecting surface itself in the second. The transition from one form of result to the other can often be observed on a river or lake. While the water is thoroughly calm, it "mirrors" the objects on its shores; and then, if a breeze ruffles it gently, we can notice how the images are distorted and broken up, until we perceive finally only the light and shade and irregularities of the water surface itself. We shall begin by discussing the reflection of light from smooth or polished surfaces, and shall first suppose them to be plane.

## IMAGES SEEN IN PLANE MIRRORS

**196.** The diagram (Fig. 68) represents a cone of light *ABCP* (see § 189) radiated from a small area *A* in a luminous source, reflected by the plane mirror *MM*, and reaching the pupil of an eye at *P*. Direct experiment proves that the reflected portion *CBP* is part of a cone whose vertex is at $A_1$, a point so chosen that the reflecting surface is perpendicular to $AA_1$ and bisects its length (Ex. 118). As the eye is moved about, the light that it receives by way of the mirror is continually identical with that which it might receive in the same position from a small luminous area at $A_1$, the mirror being removed. "The **image** of *A* is at $A_1$," to use the common phrase.

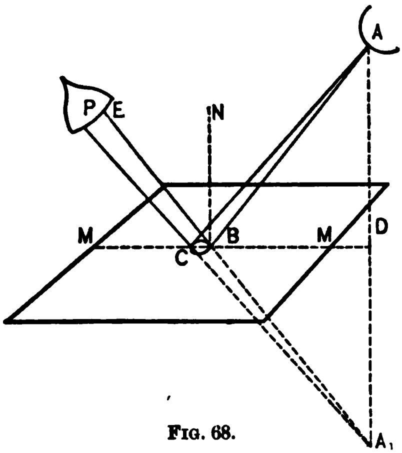

Fig. 68.

The rule for the sudden change of direction impressed upon each portion of light by the reflection follows at once from the experimental result. Taking the portion of the cone represented by *AB*, its direction after reflection must pass through $A_1$, when prolonged backward, else it would not appear to be radiated from that point. Then in the right triangles *ABD* and $A_1DB$, *BD* is common; and *AD* is equal to $A_1D$, according to the experimental evidence. Hence the angle *BAD* is equal to the angle

$BA_1D$, and a similar relation holds for any other pair of triangles, if $B$ is chosen elsewhere in the section of the cone $ABC$ by the plane $MM$. The usual statement of the rule connects the equal angles with a line such as $BN$, drawn perpendicular to the reflecting surface at the point where the particular portion of light is reflected. The angle $ABN$ is known as the **angle of incidence,** $AB$ being "incident light"; and the angle $NBE$ is called the **angle of reflection,** $BE$ being "reflected light." The two angles are evidently equal on opposite sides of $BN$, and lie in the plane of the triangle $ABA_1$, which is spoken of as the **plane of incidence.** Finally, therefore, the rule expressing the change of direction when light is reflected from a plane surface can be put in these terms: The angle of reflection is equal to the angle of incidence, and both are contained in the plane of incidence.

Show that observed results justify the application of this rule if $A$ is an *illuminated* source of light (see § 187).

**197.** The equality of these two angles, and the fact that they lie in one plane, can be established directly with great precision by measuring the "angular distance" between a star and its image seen by reflection. The general plan of such a measurement is indicated in Fig. 69, where $S$ represents a star, $OH$ a horizontal plane, and $OS_1$ the direction in which the image of the star appears by reflection in a dish of mercury $M$. The (angular) elevation of $S$ above the horizon is measured

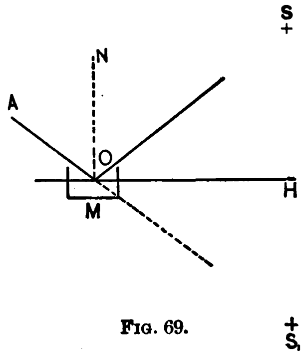


FIG. 69.

by an observer at $O$; also the angle between the direction $OS$ and $OS_1$. The results show that $SOS_1$ is a vertical plane, and that the angle $SOS_1$ is twice the angle $SOH$; hence the equality of $NOS$ and $NOA$ follows, $ON$ being the vertical at $O$.

After it is known that the angles of incidence and reflection are equal, the plan just described can be employed in determining the altitude of a star, where the view of the horizon is obstructed, and therefore the angle $SOH$ cannot be measured directly. Having observed the angle $SOS_1$ with the aid of the mercury, it is divided by two; this is the method of finding altitudes with an "artificial horizon."

What advantage do you recognize in selecting mercury rather than a solid mirror?

The above two ways of discovering the rule for reflection illustrate how such matters may be approached from different sides. Sometimes our experiments attack directly the magnitude that we desire to know, like the change of direction by reflection here; in other cases, simple (or even complicated) consequences of an unknown rule are more accessible to observation, and then we seek to infer what the rule must be, in order to produce them. Thus the known location of the image is the foundation of the argument by which we have concluded that the angles of incidence and reflection are equal and lie in one plane.

Assume the rule to be known, and put into form the proof that the image of $A$ (Fig. 68) is always at $A_1$, as a consequence of that rule.

Consider the following discoveries in Physics, and express your judgment in each instance, whether the rule was established directly or inferred indirectly: Boyle's

law relating to gas-pressure; Pascal's law about pressure in fluids; Newton's law of inverse square; weight at sea-level becomes less as we approach the equator; the speed of a body falling freely from rest grows uniformly with the time during which it has fallen.

## LIGHT SCATTERED BY REFLECTION

**198.** The simplified case of reflection introduced in § 196 furnishes a key to the whole subject; and what remains to do is chiefly to indicate the manner of applying the rule found there, in connecting and explaining other observed results. It should be clear, to begin with, from the actual circumstances of Experiment 118, how to proceed where the source of light must be thought of as including many small parts. The larger image is then built up as an aggregate of pieces, each corresponding to a small part of the source. When drawings are to be made, the process is shortened by noticing how regular outlines are repeated in the image, but with the kind of inversion familiar from the use of looking-glasses.

Now an examination of Fig. 68 (§ 196) will show that the position of the eye, the size of the source, and its distance from the mirror determine what area the latter must have in order to give a complete image of a large object. You cannot ordinarily "see yourself at full length" in a pocket mirror. Before such extended images can be perfectly formed, therefore, a definite part of the reflecting surface must lie in one plane. If the area concerned in a particular reflection departs slightly from this condition, the image will be to some extent distorted in comparison with that which would be seen in a perfectly plane mirror; cheap looking-glasses are likely

to exhibit defects of that order. The effects of large but regular departures from a plane surface, such as we find in "curved mirrors," are themselves regular, and can be treated systematically; we shall have something to do with that case presently; but where the surface is rough, the reflection that occurs must take place at minute facets, irregularly disposed and tilted up at all angles. Neighboring small portions of light are then reflected in widely differing directions, the mosaic pattern of the image is lost in fragments, none of which is large enough to be distinguishable in outline.

These conditions contribute to the observed consequences of illuminating bodies that have not regular and smooth or polished surfaces. Many irregularities will be contained within the circumference of a circle, say 0.2 cm. in diameter, taken on such a surface, and light can very well be reflected into the pupil of an eye looking at the circle from any position. The case is like that of light radiated from such a small area in a luminous surface (see Fig. 59, § 189), and we see the illuminated surface that "scatters" light, in the same sense that we see a luminous body. In both instances, we refer light to a source toward which it converges as we trace its course backward; and just so the eye $P$ "sees" the image at $A_1$ (see Fig. 68, § 196).

The process which is of the character that renders objects illuminated is termed **diffuse reflection,** as opposed to the **regular reflection** that results in the formation of recognizable images. It should be noted, however, that diffuse reflection is regular, and follows the rule of § 196; but it is not coördinated and coherent over larger areas. There are certain amounts of light diffusely reflected, even by highly polished surfaces, else we should not see them.

## REFLECTING POWER

**199.** What proportion of the incident light is regularly reflected depends upon the material of the reflecting surface and its state, of course, as these determine the polish; but the result varies in two other respects with the material. Pieces of clear white glass, for example, are more inconspicuous in a tumbler of water than they are in the air; and, in general, the *combination* of reflecting surface and substance surrounding it, in which the light is on meeting it, helps to decide what proportion is reflected. In the second place, materials are affected differently as regards the light which they reflect, by changes in the angle of incidence. The comparative behavior of water, plate glass, and mercury is shown in the table, where the numbers indicate light reflected, supposing 100 parts are incident.

REFLECTING POWER (in Air)

| Angle of Incidence | Water | Glass | Mercury |
|---|---|---|---|
| 0° to 30° | 2 | 2.5 | 60 |
| 85° | 72 | 54 | 70 |

Water and glass are practically equal for small angles, but at 85° water surpasses mercury, and leaves glass behind in the ratio $\frac{72}{54}$. The nearly constant reflecting power of mercury at all angles is characteristic of metals. The increase of regularly reflected light as the angle of incidence grows is a general rule. At "grazing incidence" (near 90°) a distinct image can often be seen in a dull knife-blade or china plate, when none is detected by reflec-

tion at small angles. The distribution of light in the "mirror effects" of a lake is altered from that in the real scene, owing to this cause, when very large and very small angles of incidence are included to form the same image.

Objects that become visible by diffuse reflection of sunlight are variously colored; there are red cloths, green grass, yellow gold, and so forth. It is pertinent to ask whether the "white light" of the sun is colored in the process of reflection itself, or by some accompanying action. The experimental answer to that question ought to be instructive (Ex. 119) in putting us on our guard against hasty conclusions; the truth is not suggested by trying only one or two substances. Notice that light is reflected from both the front and the rear surface of colored glass. It seems fair to conclude that one portion shows color because it has twice traversed the thickness of the glass. There are two reflections also in a looking-glass, one (weaker) at the first surface of the glass, and the second (stronger) from the coating of amalgam.

The image seen in a looking-glass by daylight is sometimes greenish. To what cause would you attribute the color? Does the same idea apply to cases like aniline films and polished brass?

Mirrors used for special purposes are often silvered on the *front* face, to avoid any tinge of color, and gain light in the image; polished silver reflects fully ninety per cent of the incident light, under favorable conditions.

Whatever differences may show themselves otherwise in these phenomena, they unite in impressing one lesson: Reflection is a physical process in which the substance takes part, and is not confined to the *geometrical* surface of a body (see § 79).

## MULTIPLE REFLECTION

**200.** In all that has been said thus far about illumination, and about seeing objects, the thought has been made prominent that conical or cone-like portions of light are concerned in producing the effects. We have found use for the cones of illumination (see § 190), and for the cone (often called a "pencil" of light) extending from a vertex at the source to a base on the pupil of the eye (see § 189). This idea that light is not radiated from geometrical points, nor along geometrical lines, must be insisted upon and never abandoned; light is a physical phenomenon connected with energy given off from areas, and transmitted through volumes. But we may speak of a "luminous point," or of a "point-source," if the expression be understood as a sort of shorthand for "small area of a luminous source." And, because the axis of a conical pencil shows the general direction in which the light is radiated through that volume, we may simplify diagrams by drawing such axes to represent their entire cones, and refer to the light as radiated along these lines. We shall make free use of this shorthand notation from here onward.

The light that reaches the eye may have been reflected more than once. Two diffuse reflections are involved in seeing objects by moonlight; and, as a result of regular reflections from two mirrors in a room, it is possible to look into one and see images framed within the other. Toilet-mirrors are often arranged on that plan, and the patterns seen in the kaleidoscope are also due to **multiple reflection.** No new idea is required in tracing the course of light at repeated reflections, since the same rule applies at each stage. But in explaining particular effects observed, or

in working out consequences by drawing, the readiest method is to treat each successive image found as a real source for the next reflection (see §§ 193, 196, 198). This conception of "convergence-points" for light as effective sources of it is a valuable aid in accounting for the action of many optical instruments.

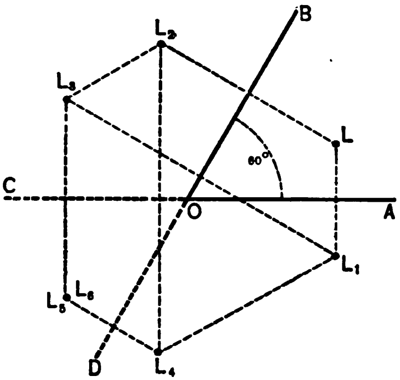

Fig. 70.

Repeated reflection of light from a *luminous point* $L$ (Fig. 70) by surfaces $OA$ and $OB$, inclined at an angle of 60°, gives a group of images as shown (Ex. 120). In cases like this, where the inclination is an aliquot part of 360°, two images (here $L_5$ and $L_6$) are coincident, and the group is closed.

Show that the group consisting of $L$ and its images lie on a circle described with $O$ as centre. In what position must an eye be, to see the images located as in the diagram? How does the result differ, when the inclination is not contained without remainder in 360°?

A practical limit to the number of reflections is set by the weakening of the available light; the images are finally not bright enough to be visible. What is the consequence when one image falls in a region like $COD$?

Where in the diagram are images of the lines $LL_1$, $LL_2$, and $L_2L_3$? Why is there no image of the line $L_1L_3$?

Prove that the direction of any portion of light is not changed by two reflections at parallel surfaces.

## REFLECTION FROM CONCAVE MIRRORS

**201.** When a pencil of light falls upon a reflecting surface that is curved, the perpendiculars corresponding to *BN* (Fig. 68, § 196) are no longer parallel at different parts of the surface, but the changes thus introduced into the angles of incidence are regular if the curvature is regular, and at any one place we are still at liberty to suppose the angle of reflection equal to its angle of incidence, because consequences calculated on that basis agree with results actually observed. The plane of incidence at each point of the reflecting surface contains the direction of the light incident there, and the perpendicular to the surface at that point. The curved mirrors that we shall consider more particularly are spherical, and their sections in plane diagrams will show as circular arcs such as *BAE* (Fig. 71), the centre of the sphere being at *C*. The mirror is concave if the reflecting surface is on the side toward *C*, convex if reflection takes place at the outside surface. Let the reflecting surface be concave, and symmetrical about *CA*, which we shall call the **axis** of the mirror; then *A* is the middle point of *BAE*, and the diagram may represent *any* plane containing the axis.

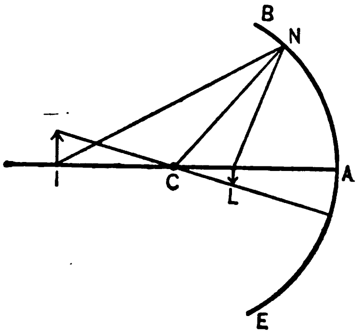

FIG. 71.

If a luminous point is situated at *C*, all the light from it that is reflected from the mirror must converge again upon

*C*, because the radii of a sphere are everywhere perpendicular to its surface, and the (equal) angles of incidence and reflection both vanish (Ex. 121). Moving the luminous point inward along *AC* to *L*, the light from it reflected at *N* will cross the axis at some point *I* outside *C*, since *LN* and *NI* must fall on opposite sides of the perpendicular *CN*. If the triangle *LNI* be revolved about *LI*, the point *N* will trace a ring on the mirror; and light reflected from all parts of that ring will cross the axis at the same point *I*, because of the symmetry in the arrangement. Moreover, the light from *L* that is reflected at *all* such rings included between *A* and the rim of the mirror is found to converge upon the point *I*, in the conditions of the experiment, and with sufficient accuracy for our purpose.

After the light from *L* has been united again at *I* by the crossing of its various tracks, it spreads once more as it proceeds farther toward the left. And an eye in that region, upon which part of the light falls, will refer it to the crossing-point *I* as a source, which appears then as the image of the source at *L* (see § 193, § 196). Since the light really passes through such an image, it can be used to illuminate a screen there, which will show where the spot falls, by diffusing the light received. Images of this kind are termed **real**, as contrasted with the **virtual images** seen in a plane mirror, through which the light does not actually pass, and which, therefore, cannot be "caught upon a screen" and rendered visible.

The image is visible without the screen to an eye in certain positions, but is more generally visible if received on the screen (Ex.). Explain this result.

If now the source is removed to *I*, and sends out light

to the reflecting surface, the former angles of reflection at each point like $N$ become angles of incidence and, consequently, the light meets again at $L$ after reflection, causing at that point in turn an image of the source situated at $I$. Because of this interchangeable relation between pairs of points like $I$ and $L$, they are known as **conjugate foci.**[1] We meet here one instance of the general truth that a portion of light can be sent back over the same track in the reverse direction.

But, further, any source approaching the form of a short straight line perpendicular to $CA$, and beginning at one conjugate focus, is found to give an image at the other, parallel to the source but inverted. This is brought out by the actual experiment, where a small flame is employed as the source of light.

**202.** We are now ready to make these results more definite by applying measurement to them; and the first step shall be to discover the relation connecting different pairs of **conjugate focal distances**; that is, distances from $A$ to pairs of points like $L$ and $I$ (Fig. 71) on the axis of the mirror. Having located the centre $C$ experimentally by the coincidence of a source at that point with its image, denote the measured radius of the sphere by $R$. Let the distance from $A$ to any position of the source be $S$, and $I$ the distance from $A$ to the corresponding image. The measured values are found to fit the expression,

$$\frac{1}{I}+\frac{1}{S}=\frac{2}{R}. \tag{32}$$

One focal distance of especial importance is that of the image which is conjugate to the sun as a source. This is

[1] **Attend carefully to the meaning and etymology of each word.**

known as the **principal focal distance** or the **focal length** of the mirror; we shall write $F$ instead of $I$ for that special value. In this case, $S$ is so large that its reciprocal is nearly equal to zero, and, omitting that term, we find $\frac{1}{F}=\frac{2}{R}$, or $F=\frac{R}{2}$. This result is verified by direct trial.

Supposing that the source of light is at $C$ (Fig. 72), the image is there too; and as the source moves outward to the left, the image shifts toward $A$. But though $S$ grows continually larger, $\frac{1}{S}$ can never reach the value zero and pass beyond it, and, consequently, the conjugate image cannot pass the point $F$ for which $I=\frac{R}{2}$.

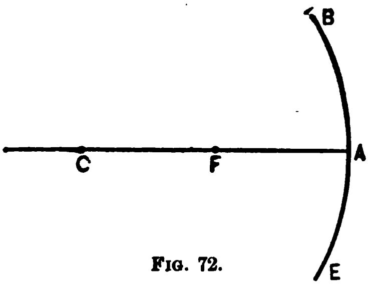

FIG. 72.

Therefore the points between $F$ and $A$ have no conjugate foci situated to the left of $F$. Are there any foci conjugate to points in $FA$, and if so, where are they? The best way, perhaps, to answer that question is to place a source between $F$ and $A$, and see what becomes of the reflected light (Ex. 122).

What value does $R$ approach, as a concave mirror decreases in curvature, and becomes more nearly a plane? Would Equation (32) suggest the relation, as we know it for plane mirrors, between the distances $S$ and $I$?

It ought to be remarked at this point, that the expression $\frac{1}{I}+\frac{1}{S}=\frac{2}{R}$, or its equivalent $\frac{1}{I}+\frac{1}{S}=\frac{1}{F}$, can be calculated and proved as a consequence of the fundamental

rule for the reflection of light (see § 197, end). But that proof is beyond our scope here, and the establishment of Equation (32) by experiment is equally instructive and valid. We shall resort to a similar empirical[1] method in other cases.

## LOCATION AND SIZE OF IMAGES

**203.** If we examine the results already obtained for any plane containing the axis of a concave spherical mirror, three directions for incident light are found especially easy to trace after reflection. Starting from a luminous point $L$ (Fig. 73), they are represented by the lines $LP, LF, LC$. The first is parallel to the axis, and stands in the same relation to the mirror as though it arrived from a very distant source like the sun or a star; it is reflected toward the principal focus at $F$. The second passes through $F$, and the action of the mirror is the same as though it started from $F$; it is returned toward the very distant focus conjugate to $F$, in a line sensibly parallel to the axis. The third passes through $C$, is treated as though it came from that point, and is returned there.

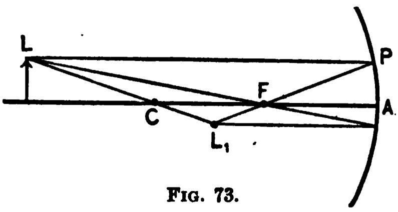

FIG. 73.

When images are to be located in advance by means of drawings made to scale, the three lines named enable us to do that readily. A real image is a common intersection toward which all the light from a luminous point converges after reflection; where two portions cross, the

[1] Empirical: based on experiment, or experience of phenomena.

others must meet also. Applying that thought to the present instance, the image of $L$ is found at $L_1$.

The difference in size between a luminous object and its image, so apparent in Experiment 121, is connected closely with their distances from the reflecting surface (Ex. 123). The reason for the observed result can be read from the diagram (Fig. 74), where $LD$ is object, and $L_1D_1$ image. Since $CA$ is perpendicular to the mirror at $A$, light incident there on its way to $L_1$ must be so reflected that the angles $LAC$ and $CAL_1$ are equal. Consequently, $DAL$ and $D_1AL_1$ are similar right triangles, and the relation is fulfilled,—

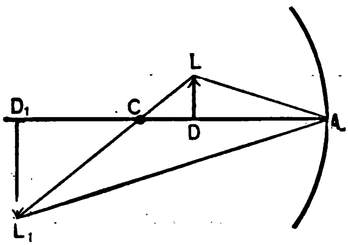


FIG. 74.

$$\frac{LD}{L_1D_1} = \frac{AD}{AD_1}.$$

What is the ratio of magnitude between a luminous *area* (perpendicular to $CA$) and its image?

It is further recognizable in the figure that object and image must be equal in angular size, *as seen from C or A*. Why could even a perfect concave mirror, therefore, not bring sunlight to a focus at a *point?*

From what points will a "magnified" image like $L_1D_1$ be seen as having greater angular size than the object? Good eyes fail to separate small objects that are less than about 90 seconds of angle apart, and see them distinct from each other. Hence the greater angular distance between given points, producible by magnification, is an aid in detecting details not seen with the "naked eye."

## CHANGE OF CONVERGENCE BY REFLECTION

**204.** We have had occasion to consider light as spreading or diverging when it is radiated from a source near at hand, as parallel on reaching us from a star or the sun, and as converging upon a small area or a point (see §§ 189, 193, 201). The action of plane or curved mirrors can be readily summed up in terms of changes produced in the convergence, divergence, or parallelism of the incident light. Thus an examination of the diagrams shows at once that a concave mirror strengthens convergence by reflection at its surface. And, more definitely, when such changes are properly measured, a certain constancy in the effects of this kind is found to be characteristic of each mirror, whatever the condition of the incident light is as regards convergence, divergence, or parallelism. For purposes of measurement, we can put all three under one heading "convergence"; then divergence will take the negative sign, and a zero value will go with parallelism, because convergence and divergence are opposite states, with parallelism as a boundary between them. Let $BVA$ (Fig. 75) represent a section through a cone of light, containing the axis, $VA$; then the quotient $\frac{BA}{AV}$ is a natural measure for the convergence or slope of $BV$ toward $AV$ (positive); the equal slope of $VC$ is negative. For example, when $BA = 1$ cm. and $AV = 24$ cm., the slope is

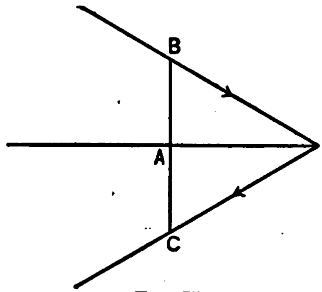

FIG. 75.

"1 to 24," in agreement with ordinary usage in speaking of grades on roads.

Apply this plan of measurement to the case of sunlight falling on a concave mirror parallel to its axis, reckoning for a point $N$ (Fig. 76) distant 1 cm. from the axis of the mirror, which is also the axis of the cone of light, and denoting, as before, the focal length by $F$. Then the convergence of the incident light can be called zero, and that of the reflected light $+\frac{1}{F}$, the latter value being closely approximate because $AN$ is short enough to be assumed straight, and perpendicular to $AC$. Hence the change of convergence (final value minus original value) is

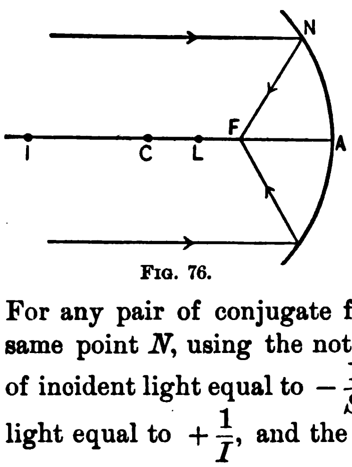

FIG. 76.

$$+\frac{1}{F}-0=+\frac{1}{F}.$$

For any pair of conjugate foci, $L$ and $I$, we have at the same point $N$, using the notation of § 202, the divergence of incident light equal to $-\frac{1}{S}$, the convergence of reflected light equal to $+\frac{1}{I}$, and the change equal to

$$\frac{1}{I}-\left(-\frac{1}{S}\right)=\frac{1}{I}+\frac{1}{S}=\frac{1}{F} \text{ (see § 202, end).}$$

Thus the mirror impresses the same change of convergence upon all light incident at the ring represented by $N$. And this ring may be adopted as a standard in comparing mirrors, because it is at *unit* distance from the axis.

Taking $N$ at some other distance, test in the same way whether light incident there is equally changed in its convergence toward the mirror axis, for any pair of conjugate foci. Is the amount of the change still $+\frac{1}{F}$?

Convince yourself that a plane mirror produces no change in the cones of light incident upon it, as regards convergence toward their axes.

**205.** It should be noticed in the experiments connected with reflection from concave mirrors, that the source of light is confined to a small area near the axis, and that the mirror is a small fraction of a complete sphere. The way in which images become distorted and blurred, if we depart widely from those conditions, can be shown without difficulty (Ex. 124).

Spherical mirrors are discussed in the text, and are probably used most frequently. But for the special purposes of astronomical telescopes, where parallel light is gathered to a focus, another form of mirror presents advantages. The reflecting surface in such instruments is so shaped that a section of it containing the axis shows a curve called a parabola, instead of a circular arc. Parabolic mirrors are sometimes used in lighthouses and searchlights, where a *reflected* beam of light is to be made nearly parallel, the source being close to the principal focus.

Some uses of concave mirrors depend upon the real images produced by them, either magnified, or smaller in size than the source of light. Other uses of them are connected with magnified virtual images. No attention has been given to the convex mirror here, because images seen with its aid are neither real nor enlarged.

# CHAPTER XIV

## SPEED OF LIGHT. REFRACTION OF LIGHT. PRISMS. LENSES

### SPEED OF LIGHT

**206.** Radiant energy in the form of sound is forwarded by air at ordinary temperatures with a speed of 340 to 350 meters a second, and with a much greater speed by water and glass (see § 180). There are no everyday experiences in the case of light, such as we find connected with sound, suggesting that it takes any time to reach us after leaving its source. Nor can experimental evidence of elementary character be furnished, that the speed with which light crosses a vacuum, or travels in glass, is definite and measurable. The reason for these facts is the great speed of light, which runs up to about $3 \times 10^{10}$ cm. a second in a vacuum or in air; we must ordinarily be satisfied with a reliable account of the processes of measurement upon which our knowledge of that speed depends, and cannot repeat them.

The first discovery and estimate of the speed with which light travels was made late in the seventeenth century by Roemer, working in Paris, who noticed its consequences when they were magnified by the scale of astronomical distances (Ref. 34). The idea underlying his reasoning is easy to comprehend; it is simply that events actually happening always at equal intervals of time will be *seen*

to happen at shorter intervals while we are moving directly toward the place where they occur, if the light by which we see them takes time to reach us. We cut off the number of seconds previously spent by the light on the distance over which we advance during one interval. Substituting sound for light, suppose a series of blasts from a steam whistle to be given at equal intervals of five minutes. With steady conditions of wind, temperature, etc., an observer standing still at a distance of two kilometers will hear the blasts *spaced* exactly five minutes apart, but each one delayed about six seconds in transmission. Immediately after hearing one blast at that station, let the same person move 340 meters directly toward the whistle before it is sounded again. Measured by what he hears, the interval is one second short of five minutes; he catches the sound on its way to his previous position. Of course this effect is reversed, for either light or sound, while the observer is moving away from the source.

Roemer's regularly recurring events were the eclipses, observable at intervals of about 42 hours, of one among Jupiter's moons; the intervals being apparently shortened or lengthened by the relative motion of the earth and Jupiter. The data were complicated for him, however, by the motions of both Jupiter and the earth in their orbits, and by uncertainty about the cause of the apparent irregularities in the eclipses. The possibility of stating the thought in simple terms now should not lead us to underestimate Roemer's success in disentangling his conclusion as to the part played by the finite speed at which light travels.

If we multiply speed ($V$) by time of travel ($T$), we obtain the distance travelled ($D$), the relation being

given in symbols as $D = VT$. When $D$ is the distance of the earth from the sun, $T$ the time light takes in travelling that distance, and $V$ the speed of light, $V$ can be calculated if we know $D$ and $T$; it is their quotient, $\frac{D}{T}$. Astronomy rendered Physics the service of measuring the speed of light in this way. The numerical values are $T = 500$ seconds, $D = 149 \times 10^{11}$ cm. Make trial how closely these fit the (rounded) number for the speed of light, $V = 3 \times 10^{10}$ cm. a second. But at the present time, the speed of light can be measured on the earth, between two points only a few hundred meters apart (Ref. 35). And this speed, in connection with the time $T$, supplies astronomers with a new determination of the distance from the earth to the sun, which is an important element to them.

## REFRACTION: CHANGE OF SPEED

**207.** When sound enters water or glass from air, its speed is greatly quickened. What change (if any) is produced in the speed of light under similar circumstances? This important question remained unanswered until the middle of the nineteenth century, or nearly two hundred years after Roemer's discovery; when Foucault measured the speed of light in water, and found it to be only about $\frac{3}{4}$ of the value for air or a vacuum (Ref. 36). On entering glass from air the speed is reduced in about the ratio $\frac{2}{3}$; the material itself of water or glass *carries* the sound, but *hinders* the passage of light, and the same is true of other transparent substances; the speed of light is less in them than in "free space." These alterations of speed are intimately related to changes in direction that

are observed when light crosses the boundary between one substance and another. But before we can bring out that connection definitely, we must first advance to the point of stating the rule that the changes of direction follow.

A small cone of light proceeding from *L* (Fig. 77) passes through air, and meets water obliquely at the surface *BD*. Having given some account of the portion that is reflected in such cases, we are now to consider the part that is allowed to pass through the second substance — water in the present instance. The cone-axis *LCA* is "broken" or refracted at *C*, where it enters the water, the angle *PCA* being contained in the **plane of incidence,** determined by *LC* and the perpendicular *CN* to the surface *BD* at *C*, as it is for reflection. The **angle of incidence** *LCN* is greater than *PCA*, which is called the **angle of refraction.** If lines corresponding to *LC*, *NP*, and *CA* are drawn for other points in the section of the cone by the plane *BD*, the angles of incidence and refraction at each point always lie in one plane, and the latter is smaller. Each part of the light is "bent toward the perpendicular" (such as *NP*) on entering obliquely into a transparent solid or liquid from air (Ex. 125).

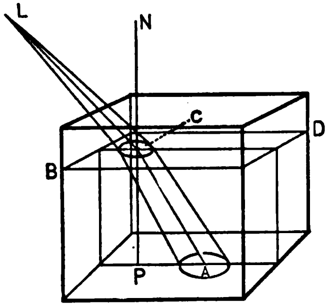

Fig. 77.

Although the general features of this action must have been observed for centuries, the rule expressing definitely the relative magnitude of the inclinations to the perpen-

dicular was first discovered by Snell in 1621, and did not become widely known until published by Descartes in 1637 (Ref. 37). But the simpler rule of equality for the angles of incidence and reflection was recognized among the Greeks in the time of Euclid.

**208.** We shall put the rule for refraction into a form that applies to two (given) transparent substances, the boundary between them being either plane or regularly curved. The elements to be introduced are (1) the perpendicular to that boundary at any point, (2) the direction in which light is incident there (given by the angle of incidence), and (3) the direction in which it continues as refracted light (given by the angle of refraction). Take the complete result in two parts: —

(1) The angles of incidence and refraction are on opposite sides of the perpendicular, and are contained in one plane.

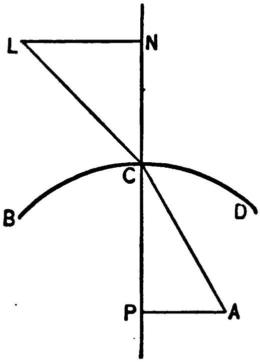

Fig. 78.

(2) The inclinations of the incident and the refracted light to the perpendicular are such that the distances travelled at right angles to the perpendicular are in a constant ratio, if we compare equal lengths along the track of the light in the two substances. The value of this ratio changes, of course, according to the substances used.

Let *BD* (Fig. 78) represent a section of the boundary surface by the plane of incidence, *LC* the incident light, *CA* its continuation as refracted light, and *NP* the perpendicular to *BD* at *C*. Having

taken $CL$ and $CA$ (any) equal lengths, the "law of refraction" requires that the ratio $\frac{LN}{PA}$ shall be constant for all angles of incidence, unless the materials in contact at $BD$ are changed.

To prevent misunderstanding about the scope of this rule, however, it must be qualified in three respects: —

(1) The ratios such as $\frac{LN}{PA}$ change, not only with the materials, but also with the *color of the incident light.* For the present, we can regard that ratio as being an average for all colors.

(2) If light is incident perpendicularly on the boundary surface, there is *no change of direction*, and the rule does not apply. Light approaching $BD$ in the direction $NC$ continues in $CP$.

(3) There is a peculiar action within some crystals, which sometimes throws the refracted light out of the plane of incidence. We shall not deal with such substances in our work here.

**209.** The connecting link between the changes of speed and the changes of direction in the light, that was spoken of in § 207, can now be supplied. The constant ratio made prominent by the rule for refraction is also the ratio of the speeds at which light passes through the two substances. For example, if $BD$ (Fig. 78) represents the plane surface separating water and air in Experiment 125, the ratio $\frac{LN}{PA}$ is found to have the value $\frac{4}{3}$, which agrees with the result of Foucault already quoted. Note that the numerator belongs to the incident light, and the denominator to the light after refraction; the ratio is to be

written $\frac{3}{4}$ if light enters air, coming from water. The quotient of the speed of light in a vacuum by its speed in any material is known as the **index of refraction** for that material. Thus the index of refraction for water is 1.33; that for glass is about 1.5, though it varies with the composition of the glass.

INDEX OF REFRACTION (Average)

| Substance | Index of Refraction | Specific Weight |
|---|---|---|
| Alcohol | 1.36 | 0.79 |
| Turpentine | 1.47 | 0.87 |
| Water | 1.33 | 1.00 |
| Glass | 1.53 | 2.58 |
| Quartz | 1.54 | 2.65 |
| Calcspar | 1.66 | 2. 1 |
| Diamond | 2.47 | 3.49 |

The extent to which transparent substances slacken the speed of light as it passes through them does not conform to any general rule. Although comparison of two materials sometimes shows greater specific weight accompanying larger index of refraction, there is no recognizable numerical relation between the two properties, and the order of magnitude is occasionally reversed, as the table shows; the index of refraction for water is less than that for turpentine or alcohol, though water is specifically heavier.

## TOTAL REFLECTION

**210.** Light may spread from an object under water, and reach an eye above after being refracted at the free surface. If $L$ (Fig. 79) is part of such an object, the eye

at $P$ will receive from it a cone of light somewhat as indicated in the diagram, and refer it to an image $L_1$ at its vertex as its source (Ex. 126). Experiment shows the divergence in the cone of refracted light to be such that $L_1$ is closer to the surface than $L$; and general observation confirms that conclusion — clear water always seems shallower than it is, as we look at the bed of a lake or stream. Even though the line of sight is vertical, the same effect is produced; and the diagram offers a conclusive reason for that particular result. The cone $LAB$, spreading upward, must open out wider in passing the free surface, and converge now to a point $L'$ above its original vertex.

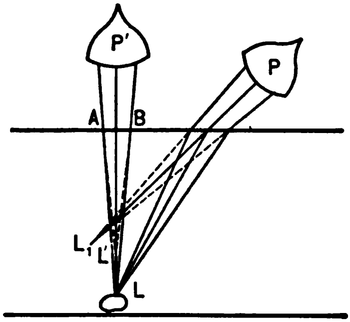

FIG. 79.

But light thus radiated toward a surface separating water and air does not always cross the boundary and emerge into the air; and a similar result can be obtained when glass is used instead of water (Ex. 127). The process of reflection that replaces refraction in these circumstances throws back nearly all of the incident light, and has been named **total reflection** in consequence. We shall examine the conditions under which refraction passes into total reflection.

**211.** Let $BD$ (Fig. 80) represent the free surface of water into which light is passing at $C$ from the air above. Suppose first that the cone of illumination (see § 190) for $C$ is $CMN$, here shown in vertical section, everything being

symmetrical about the vertical line $CV$. After refraction in entering the water, the light will be "condensed" into the cone $CEF$, $EF$ being drawn to scale and equal to $\frac{3}{4}$ of $MN$, as chords in the same circle (see § 208). The cones containing the incident and the refracted light will grow or decrease together, but $CEF$ will always be smaller than $CMN$. The same general relation exists if there is no full cone of illumination, but only a pair of small luminous sources on the circumference of the circle at $M$ and $N$. They will send light through $C$ to $E$ and $F$; and if they are moved apart on the circumference almost to $B$ and $D$, their light enters the water at $C$ on the lines $CH$ and $CG$ ($GH = \frac{3}{4}BD$). That is, all the light which could enter the water through $C$, from a cone of illumination filling the whole hemisphere $BMND$, would be confined in the water to the cone $GCH$; no light admitted at $C$ would traverse the regions $CBG$ and $CDH$. Consequently, using the idea of sending light back upon its track (see § 201, end), light incident at $C$ from sources at $G$ and $H$ would be refracted into $CD$ and $CB$; and, if those sources are moved still farther toward $B$ and $D$, the light from them has no "place to go to" by *refraction* at $C$. It does pass beyond (*i.e.* below) the lines $CD$ and $CB$, however, and is turned back into the water by *total reflec-*

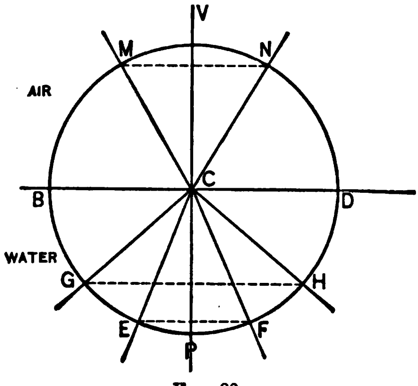

FIG. 80.

*tion* at *C*. The angle *PCH* (or *PCG*) forming the boundary between the two processes is termed the **critical angle.** *GH* is the chord of twice the critical angle; and the length of *GH*, multiplied by the index of refraction for water, gives the diameter *BD* of the circle, which may, of course, be drawn with any radius. The critical angle for refraction from water into air is 48° 30′ (Ex. 128).

Make a drawing to scale for refraction from glass to air, and determine the critical angle with a protractor, assuming the index of refraction for glass to be 1.5. In Experiment 127, find how much greater the angle of incidence on the hypotenuse-face was than the critical angle. Why is light not totally reflected when the hypotenuse-face is wetted or greased, nor from a glass plate under water?

## ATMOSPHERIC REFRACTION

**212.** We have treated the speed of light in air and in a vacuum as equal; but, in fact, light slackens speed on reaching our atmosphere, the effect increasing as it passes through layers of greater density (see § 177) until the change amounts to $9 \times 10^6$ cm. a second in air at standard pressure and temperature. Yet this is only 0.0003 of the value for a vacuum (*i.e.* interplanetary regions), and may ordinarily be neglected. "Atmospheric refraction" affects the observed positions of stars noticeably, however, especially when they are near the horizon, where the angular displacement attains values from one-quarter to one-half a degree.

Draw a diagram, and illustrate that the altitude of a star is normally increased by atmospheric refraction. Given that the angular displacement on the horizon is 35

minutes (of arc), by how many minutes (of time) is sunset apparently delayed? Show that the change of direction in light by the time it reaches the earth's surface at a particular locality is the same as though it passed directly from a vacuum into the lowest layer of air (see § 209).

The "optical differences" (or differences as regards speed of light) between neighboring layers of air produce the phenomenon called "mirage," and other curious illusions. Total reflection can occur with small optical differences, provided that the light, if refracted, would move faster than the incident light, and that the angle of incidence approaches very close to 90°. Hence light may be totally reflected as shown at *A* (Fig. 81), from a stratum of air caused in any way to be warmer than that above it. The surface *BC* is sometimes heated soil or pavement; or, again, it may be a hot plate of metal, making the layer of air next to it hotter than those above. The effect at very oblique incidence is to give a mirror-image of *D*, and produce the impression that water is present.

FIG. 81.

Even when the circumstances of total reflection are absent, small optical differences, due to unequal heating or concentration within what is nominally the same material, produce *partial* reflections, and enable us to see the outlines of convection currents in air and water, or currents active in making a solution. Some reflection takes place at every boundary where the speed of light is altered.

## EFFECTS OF TRANSPARENT PLATES

**213.** When we look through a window-pane, or through a spectacle-lens, the light that reaches our eyes has been refracted twice, — on emerging from the glass as well as on entering it. The consequences of two such refractions that we are now to touch upon differ considerably according to the attendant conditions, so that it is advisable to separate three types of case: (1) the refracting surfaces are plane and parallel (plates); (2) they are plane but inclined to each other (prisms); (3) they are inclined and one at least is curved (lenses). We shall use the words "plate," "prism," "lens," in the senses here indicated.

Let *BDEF* (Fig. 82) represent a glass plate in air, the section being taken in the plane of incidence for the light *LC*. Then the emergent light *AR* is parallel to *LC*, because the perpendiculars *NP* and $N_1P_1$ are parallel, and the refraction at *A* just reverses the change of direction at *C*. The distance apart of the parallels *LC* and *AR* evidently depends on the thickness of the plate. In general, then, any portion of light that passes through a plate is rendered parallel to its original direction, if it is restored to its original speed; and that condition is met, if the same substance is in contact with both faces of the plate.

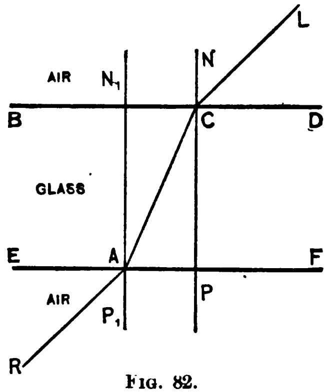

FIG. 82.

Suppose that *BD* and *EF* are parallel plates of glass,

the space between them being filled with water. If light passes through such a tank as it stands in air, would the directions $LC$ and $AR$ still be parallel?

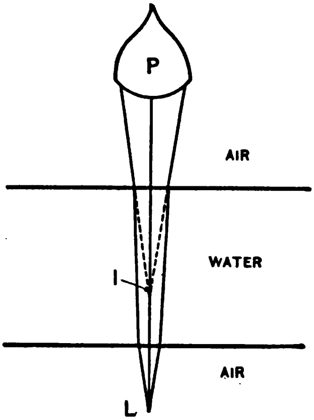


FIG. 83.

When we look through a thick plate, either perpendicularly or obliquely, at objects on the farther side, we see images of them that are nearer to the eye than the objects themselves (Ex. 129). The diagram (Fig. 83) exhibits the relations for nearly perpendicular incidence within the cones of light that reach the eye. Why is this effect not prominent in looking at a landscape through a window?

## EFFECTS OF PRISMS

**214.** The effective faces through which light enters and leaves a glass prism are represented by $EA$ and $EB$ (Fig. 84). The angle made with each other by these faces is the "refracting angle" of the prism, and their line of intersection $EE_1$ is its "refracting edge." The axis (twice broken) of a cone of light proceeding from a source at $L$ to an eye at $P$ is shown by $LCDP$. We shall suppose that this axis lies in a plane perpendicular to the refracting edge, and that the prism stands in air. If the "white light" of the sun or the electric arc is employed, two general effects are observed (Ex. 130): —

(1) The light received by the eye appears to come from some such direction as $L_1$, making a considerable angle with the original direction $LC$. This change of direction is the **deviation** produced by the prism.

(2) The light appears spread out into a colored patch, instead of yielding a clear white image of $L$. This feature in the result is the **dispersion** caused by the prism.

The fact that dispersion accompanies refraction was discovered by Newton in 1666 (Ref. 38). It furnishes experimental evidence for one limitation that has been put upon the rule concerning refraction (see § 208, end, (1)).

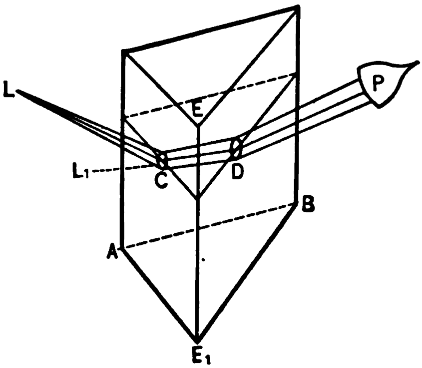

Fig. 84.

Draw a diagram to scale, representing the course of the cone-axis in the plane of incidence for the case of Fig. 84, and determine the direction and the amount of the deviation, assuming a refracting angle of 30°, and an *average* index of refraction 1.5. Indicate on this diagram the relative position of the red and the blue color as you have observed them. Which is deviated more, and which less than the average?

Does a prism always deviate light "away from its refracting angle" (Ex. 131)? Explain the result that you find.

What grounds do you discover for thinking: (1) that a

prism forms a *series* of images, one for each color? (2) that dispersion is only a separation of white light into elements already present in it, but mingled (Ex. 132)?

## EFFECTS OF LENSES

**215.** We shall consider the curved faces of lenses to be spherical. A very common form, shown in outline by *A C* (Fig. 85), is the **biconvex lens**, having both faces alike. The line joining the centres, *D* and *E*, of the equal spheres is the **axis** of the lens, which is symmetrical round that line. A lens with this outline, made of glass and used in air, brings sunlight that falls upon it parallel to its axis into a focus — it is a "burning glass" (Ex. 133).

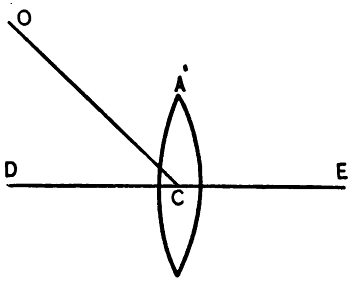


FIG. 85.

A lens similarly symmetrical otherwise, but **biconcave**, sends out sunlight that has passed through it as a spreading sheaf of light — it is a diverging lens. Recollect, however, that these effects of such biconvex and biconcave lenses are due to the retarded speed of light in glass as compared with air (Ex. 134).

We shall confine ourselves rather closely to the biconvex lens (of glass, in air), and shall follow the model in our treatment of the concave mirror (see §§ 201–204), both as to the thought and as to the notation. Thus *F* denotes principal focal distance, or **focal length**; *S* and *I* are distances to source and image, respectively; and all

such distances are measured from $C$, the **centre** of the lens, along its axis (Ex. 135).

Using a small source of light close to the axis, does a biconvex lens unite practically all the refracted light in a well-defined image? Is the result affected noticeably if the source is placed on a line $CO$ (Fig. 85), inclined 45° to the axis?

What is the range of *real* conjugate foci? What happens outside of that range? Are the real images erect or inverted? In what common use of a biconvex lens do you see erect images?

Do the pairs of conjugate focal distances, $S$ and $I$, satisfy Equation (32) (§ 202), in either form of it? At what positions are source and image equidistant from $C$? How could you use a biconvex lens to render light "parallel," that comes from a small source near at hand? Recall any instances of such use that you have met.

In what way are the *areas* of source and image related to their distances from $C$?

What directions of the incident light are especially suitable for locating the positions of images on drawings? What becomes of the light incident in the direction whose prolongation passes through $C$? How are the angular sizes of image and object related, as seen from $C$? Would sunlight be focussed to a *point* by a perfect lens?

Within what cone must an eye be situated, in order to see a real image without the aid of a screen? How does receiving the image on a screen influence the result?

Can the idea of § 204 be applied to biconvex lenses?

Which parts of Experiment 135 are like getting an image on the ground glass of a photographic camera?

Two lenses (or combinations of lenses) are usually found

in a projection lantern; the "condenser" and the "projection lens." Determine by trial what share the condenser has in the magnification of the image, and its sharpness of outline (Ex. 136).

## OPTICAL EFFECT OF THE EYE

**216.** In the optical part of them, our eyes produce an effect similar to that of a converging lens, real images being received on a screen called the retina, where the *sensation* of light begins. Distinct images of objects at various distances are obtained on the ground glass of a camera by regulating the position of that screen with reference to the lenses. The peculiar internal arrangements of the eye, though different from the "bellows-action" of the camera, are its equivalent in giving clear outline to images of both far objects and near ones. The most important feature in this adjustment is the muscular control over the curvature of the "crystalline lens," which is called **accommodation** (Ref. 39). Changes in curvature alter the focal length of the combination in the eye, and, therefore, the conjugate focal distance in front of it corresponding to the (nearly) fixed position of the retina.

But the range of accommodation is limited; in normal eyes, the effort to see distinctly objects as close as 10 or 12 cm. is soon felt as tiring, and from 25 to 30 cm. is the proper distance for sustained use of the eye in reading. The limits of accommodation are moved when eyes become "near-sighted" or "far-sighted." In the latter case, the distinct vision of remote objects is still possible, but the muscles cannot bring about the greater curvature required in seeing things 20 or 30 cm. away. For near-sighted eyes both limits lie closer; in marked

cases, distinct images can be formed of objects that are within 4 or 5 cm. of the eye, but vision becomes ineffective for distances of a few meters.

The essential element in distinguishing the smaller details and markings of things that are seen is *angular* size (see § 203, end). And if the range of accommodation extended to within 1 cm. from the eye, the angle subtended by an object could be increased (that is, we could "magnify" it) merely by moving it nearer to our eyes from a standard position 25 cm. away. In fact, the unassisted vision of very near-sighted persons does magnify objects appreciably as compared with normal eyes. The great service which magnifying glasses, telescopes, opera-glasses, and compound microscopes render is that of presenting to the eye images at a distance of 25 cm. or more, which retain an angular size the object would have if held far too close for us to see it. We shall illustrate several ways in which this is done with the aid of both real and virtual images.

## CONTRIVANCES FOR MAGNIFYING

**217.** Sun-spots may be observed in a real image of the sun, formed on a screen by a biconvex lens with a focal length 5 meters. Let $L$ (Fig. 86) represent such a lens, its axis being directed toward the centre of the sun's disk. The image received on a semitransparent

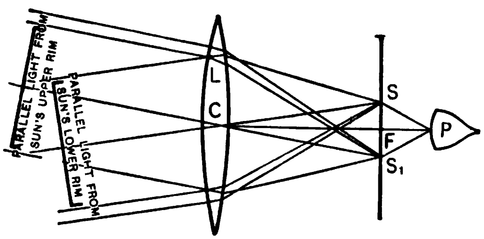


FIG. 86.

screen $SS_1$, perpendicular to the axis at the principal focus $F$, has an angular size of 32 minutes (see § 190, end, (2)), equal to that of the sun itself, as seen from $C$, and an actual diameter of about 4.5 cm. And an eye at $P$ ($FP = 25$ cm.) sees the image with angular size $SPS_1$. But the angle at $P$ is greater than that at $C$ in very nearly the ratio $\frac{CF}{PF} = \frac{500}{25} = 20$; the lens magnifies the sun 20 times.

Notice that the whole face of the lens receives a cylinder of parallel light from each part of the sun's disk, and that each cylinder has its own focus. The complete group of such foci make up the round image of the sun upon the screen. Since the entire cylinder of light is collected at its focus, the "light-gathering" power of a lens increases with its area. An image of the sun is bright to excess, but the greater brightness of the image formed by large lenses is an advantage when the source is a faint star or planet. The diagram indicates only the *extreme* cylinders, from the highest and the lowest part of the rim (see Fig. 66, § 193). Verify for yourself by calculation that the diameter of the sun's image is between 4 cm. and 5 cm.

The magnification can be pushed a little beyond 20 in this case, by "forcing" the accommodation of the eye and moving it nearer to the screen, thus increasing the angle $SPS_1$. But, without calling upon the accommodation at all, the magnification can be carried still further by looking at the image $SS_1$ through a second biconvex lens, held in such a position that it gives a *virtual* image of $SS_1$ (Ex. 137).

Having made the necessary measurements with a definite arrangement of this kind, draw a diagram to

scale, showing the passage of the light through the second lens, and compare the angular magnitude of the final image with that of the original object, supposing both to be seen from $C_1$, the centre of the second lens.

What effect will be produced at the eye, if a distant object (say the moon) is looked at with such an arrangement of two lenses, the distance $CC_1$ being equal to $(F + F_1)$, the sum of their focal lengths? Do you see any advantage in choosing the second lens of considerably shorter focus than the first?

The scheme here described is the foundation of the astronomical refracting telescope. If the first real image ($SS_1$, Fig. 86) is formed with a concave mirror, as it may be, of course, we have the plan of the astronomical reflecting telescope in one form. When the first lens ($LC$, Fig. 86) is very close to the object of which it gives a real image at $SS_1$, to be viewed with a second lens, the arrangement is typical of the compound microscope. The excellence of all three instruments in their perfected modern shape is the result of careful thought and experiment devoted to improving them, and of wonderful mechanical skill. But the main idea is as simple as we have tried to make it appear (Ref. 40).

# CHAPTER XV

## ABSORPTION OF LIGHT. COLOR

**218.** In the chapters devoted to the reflection and the refraction of light, we have carried out the first divisions of the plan announced in § 190. Having given there what seems an adequate account for our present purpose of the two parts in the incident light that continue their course without appearing to be changed, except in direction, the effects remaining to be spoken of are those which become prominent because light-energy is transformed. We shall begin by examining light that has passed through colored glass, and changed its own color from "white" to red, or green, or yellow, or blue, as the case may be. Has the incident light gained, or lost, in the process?

### PRISMATIC ANALYSIS: ABSORPTION

When white light falls directly upon a prism of colorless glass, as in Experiment 130, it is separated or dispersed into its several parts, and a colored band or spectrum is seen, in which known colors are arranged in a regular order. Light that is already colored can be dispersed by a prism, too; and comparison of the spectrum then formed with the standard spectrum yielded by white light will show which has the fuller series of colors (Ex. 138). The incident light being derived from the same source, the absence of certain colors from one spectrum is

good evidence of absorption along the track of that light, *provided that the light turned back by reflection is white,* like the incident light. From these observations we can conclude, in a large group of cases at least, that what is recognized as the color of a substance is the color of the light which it transmits, and that the incident white light becomes colored in passing through, because some parts of it are absorbed.

What would result if the condition indicated in italics were not fulfilled? Have our experiments included any transparent substances that appear not to fulfil it (see § 199)? Be ready to notice other cases where all colors of light are not reflected equally. Substances that show one color in the light which they reflect, and another in that which they transmit, are often said to have "metallic lustre."

The coloring of diffusely reflected light can be connected readily with absorption, if we remember that a roughened surface is especially fitted to "entangle" light among its irregularities, reflecting some that has penetrated to small distances, and been colored by absorption during the passage in and out again.

**219.** Where a colored substance only acts upon the light that is supplied, absorbing it, reflecting it, or allowing it to pass, color cannot be shown except to the extent that light of the proper composition is furnished by the source. A blue material will "lose its color" when illuminated with a light that contains no blue, if it owes its blueness to light that it transmits (Ex. 139). It is a well-known fact that the hues of some flowers, and the colors of some materials, are different by daylight and by "artificial light"; and the reason for such results becomes clear

when the light from incandescent lamps, kerosene lamps, gas-flames, and the electric arc is examined with a prism and separated into the elements that compose it (Ex. 140).

Recall some instances that you have observed of color altering with illumination, and see how they agree with the prism's evidence about common sources of light.

What account can you give of the additions that are made to the spectrum of a source, as its temperature is raised?

Extended use is made of the prism in the two ways of which examples have just been given, as a means of identifying substances by their action toward light. Some produce characteristic absorption in limited regions of the sunlight spectrum, which then appears darkened where it is crossed by "absorption bands." And the light radiated by glowing gases or vapors, when separated by dispersion in the prism, is often seen to consist of a few colors only, which show as bright bands or lines, the intervals corresponding to the absent colors of light being left dark.

We have before us here the main ideas of **spectrum analysis**, which is now relied upon to increase our knowledge about the conditions of stars, while it is also a searching method of investigation for sources of light and substances that are near at hand (Ref. 41).

## COLOR DUE TO SUSPENDED PARTICLES

**220.** There are other causes of color besides dispersion and absorption, some of which are too difficult of statement to prove satisfactory material for our purpose. A good instance is the colors of soap-bubbles, although the phenomena are familiar to children. But white light is

sometimes colored in transmission, where it passes among a large number of minute particles, suspended in a gas like air, or in a liquid like water. And the action is in so far simple that it seems to depend upon reflection of the more refrangible light (near the blue end of the spectrum) in greater proportion than the less refrangible light (near the red end of the spectrum). On the whole, therefore, the blue predominates in the reflected light, and the red in the transmitted light (Ex. 140, *A*). The blue of the sky and of deep clear water are instances where reflected light reaches the eye after being thus sifted and changed in its proportions. The red colors of sunset, and of the sun's disk seen through the smoke of a forest fire, are the complementary result in the light that is not turned back (Ref. 42).

In refraction the speed of blue light is most changed; in the selective reflection spoken of above, blue light is turned back by particles that are fine enough to let red pass; and blue is otherwise easily hindered by absorption. Where light of any color is stopped, the general consequence is that the radiated energy is transformed into heat; but special results are added in some cases, as an equivalent for part of the light-energy. The blue light is strongly involved in the processes that give rise to these special effects, photography being one well-known instance. And the phosphorescence of substances such as calcium sulphide is noticeably stimulated by radiation like that of the sun, in which the blue light is well represented. The phosphorescence of phosphorus itself (from whose name the word is taken) and of decaying wood is apparently due to slow chemical action, and should be distinguished from the after-effects of absorbed radiation.

# MAGNETISM AND ELECTRICITY

## CHAPTER XVI

### MAGNETS. MAGNETIC PROPERTIES OF ELECTRIC CURRENTS

#### MAGNETS

**221.** Magnets have the power to attract and hold small pieces of iron or steel, and to "set" in one particular direction at each locality, when pivoted so as to turn freely. The use of the compass as a guide depends upon the presence of the second quality in its "needle"; and the attractive force between a "horseshoe magnet" and iron is familiar from childhood through its use as a plaything. We have no reliable record of the dates when these two distinctive properties of magnets were discovered.

Magnetic properties are found already developed in some ores of iron, while bedded in the earth, "natural" magnets or **lodestones** being thus obtained. By rubbing pieces of iron or steel properly with them, the former can be **magnetized**; that is, the power to attract and the tendency to take up a particular position are imparted; we can get "artificial" magnets in this way. Magnets may be *multiplied* by such a process of stroking, without appreciable loss of the quality in the original source. The process of magnetization is not one of *sharing* a constant quantity of something, as we have found the transfer of

heat to be (see § 84). No doubt the method of contact with lodestones was largely resorted to in early times; but it has been superseded by more effective ones (Ex. 141).

The tenacity with which the existing magnetic condition is retained varies considerably with the samples of iron or steel employed, making it more difficult to magnetize them — and to get rid of their magnetization — in some instances, less difficult to bring about either kind of change in others. Tempered steel is most stable in this respect, and therefore best suited for **permanent magnets**; annealed wrought iron takes on and loses magnetization readily, and is adapted to uses where repeated changes of magnetic condition are desirable. Cast iron and soft steel occupy an intermediate position, and magnets made of them are sometimes classed as **subpermanent**. The gain or loss of magnetic properties is favored by any form of mechanical jarring like a blow or tapping.

## MAGNETS: RELATION TO THE EARTH

**222.** The attraction exercised upon a small piece of iron is not equally strong all over the surface of a magnet (Ex. 142). As provided for common use, a straight **bar magnet** is nearly indifferent at the middle, and most vigorously active near the ends, and the distribution of effect in a curved **horseshoe magnet** is similar. A line drawn upon such a bar magnet, joining the regions of strongest attraction, is found to take a northerly and southerly direction when the magnet is balanced on a pivot and turns freely, the same preference for north being always shown by one end, and for south by the other. The

active centres are called **poles**; they are *regions* rather than points, but may at first be conveniently regarded as points, the line connecting them being then termed the **magnetic axis** of the bar. The pole that seeks the northerly position is the **north pole** (*i.e.* north-seeking pole) of a magnet; the **south pole** faces southward.

Speaking in general, the horizontal magnetic axis of any suspended bar magnet does not come to rest in the geographical north and south line; that is, the direction given by the meridian of longitude passing through the place where the observation is made (Ex. 143). The direction assumed by the magnetic axis is distinguished as the **magnetic meridian**, and its divergence from the geographical meridian is the **magnetic declination** for the locality. The declination is termed easterly, where the magnetic axis points east of "true" north. Within the boundaries of the United States, the range of magnetic declination is nearly 40°, from strong westerly declination in Maine to easterly in California. The line of no declination passes through Ohio and South Carolina; but it does not run along a geographical meridian, and it is slowly changing its position from year to year.

A second feature in the behavior of a magnet becomes apparent if it is free to turn in the vertical plane of the magnetic meridian, about a horizontal axis passing through its centre of weight (Ex. 144). Before the bar or wire is magnetized, it is balanced on such an axis (see § 162); but after magnetizing it, the fact observable anywhere in the United States is that the north pole of the magnet points downward at an angle with the horizontal varying from 60° to 75°. The angle now made by the magnetic axis with the horizontal (magnetic) north and south line

is the **magnetic inclination** at the place. Like declination, inclination shows irregular distribution in latitude and longitude, and slow annual changes. In the countries of the southern hemisphere, the south pole of the magnet is found to point downward.

Besides the more deliberate annual variation, magnetic declination and inclination fluctuate on a smaller scale from hour to hour, and more suddenly on a larger scale during "magnetic storms." Influences radiated from the sun seem to play a part here (Ref. 43).

## MAGNETS: RELATION TO EACH OTHER

**223.** The north and south poles of a magnet, which stand in opposed relation to a direction on the earth, are contrasted in another respect. When two magnets are brought near each other, mutual repulsion is exerted between their poles of the same name, and attraction by poles of different name (Ex. 145). If we connect this fact with the action of a magnet near the earth, it suggests at once that the latter is itself magnetized, and has a south pole (in the magnetic sense) in the north polar regions, a south pole somewhere in the Antarctic Ocean. Accepting the general suggestion, it is nevertheless evident, from what has been pointed out already, that the distribution of magnetic properties in the earth is not so regular and simple as though they were due to a bar magnet laid lengthwise along the polar axis.

The rule about attractions and repulsions is useful in detecting whether pieces of iron or steel are magnetized, when another magnet is available to make the test, without balancing them like compass needles. Unless it is

magnetized, no part of the iron or steel tested is repelled by either pole of a magnet, but it is everywhere attracted by both poles. Be careful, however, to apply both ends of the testing magnet in doubtful cases, for two or more pairs of poles can be developed in a rod, arranged as shown at $SNN_1S_1$ (Fig. 87); $N$ and $N_1$ are then called **consequent poles.** Odd numbers of poles are not found to occur.

FIG. 87.

If this bar were pivoted on a vertical axis at $O$, how would the ends $S$ and $S_1$ behave toward the north pole of the testing magnet? How toward its south pole?

We shall suppose that each magnet has no more than two poles, except when the contrary is stated; and in the ordinary case, therefore, the complete action of one magnet upon another consists of two attractions between poles of different name, and two repulsions between poles of the same name. Any such actions grow weaker as the distances apart of the active centres are increased, and push or pull will preponderate according to the relative positions of the four poles (Ex.). The two magnets may be drawn bodily toward each other by their mutual action, or they may be separated. It is noticeable that the earth exerts no force upon another magnet except to turn it, without drawing it northward or southward as a whole (Ex. 146). This means that the forces at the magnet's poles, which are practically parallel on account of the earth's dimensions, are also equal in magnitude and balance each other.

Now the magnet and the earth are jointly concerned in this result, as a heavy body and the earth are in the case of weight (see § 176). The magnet would not move if

the earth did not turn it; and the earth does not exert any influence of this sort upon an unmagnetic metal like brass. As for the earth's share in the effect, we should expect that to be sensibly equal at both ends of a magnet — which is a mere point relatively to the earth's surface. But the equality of the forces in question proves in addition that a magnet is *equally magnetic* at both its poles; or, as we say, its poles are of equal strength. The scheme of four equal and parallel forces, two in one direction, two in the other, is shown acting horizontally on the bar magnet *NS* (Fig. 88).

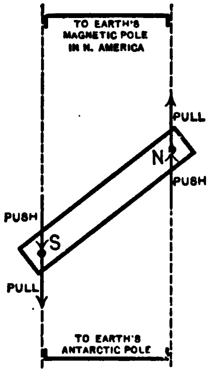


FIG. 88.

## MAGNETIC INDUCTION

**224.** Magnetic forces of attraction and repulsion are exerted through air and other gases, water and other liquids, glass, wood, and most metals, very nearly without regard to the material interposed. At the same distance, the forces are equally strong (Ex. 147). But if a rod of iron or steel is used as a carrier, magnetic effects are exhibited strongly at a distance of 75 cm. or more, that are inappreciable through other substances. Iron (and its modification, steel) are said to be especially **permeable** to magnetic influence.

Rods and bars of iron or steel that have been employed in this way register the fact by becoming magnetized in the process. Other materials do not appear to suffer these internal changes, except nickel and cobalt, where the results are much weaker. As magnetic metals, iron

and steel are in a class by themselves; and even they lose their special permeability when made red-hot (Ex. 148); but they regain it on cooling. Magnets that are developed in this process of carrying magnetic effects are described as magnetized by **induction**. Where we are able to trace the history of the steel magnets that are in use, their magnetic properties are found originating in some process of induction at some time. The "inducing magnet" for the lodestone is the earth, which is known to produce similar results in other cases, like steel or iron ships, girders, and columns of buildings, particularly if they are jarred or shaken while exposed to the earth's influence (Ex. 149). As regards the *retention* of induced magnetization, the previous remarks apply (see § 221, end). Induction is a disturbing element in testing magnetic polarity with a compass needle or other small magnet (see § 223). Where the magnet tested is relatively strong, and the testing magnet is weak or made of softer steel, the polarity of the latter is often reversed in the act of making the test (Ex. 150). Hence *repulsion* is safer than attraction to rely upon as evidence in judging polarity.

What error might reliance upon attraction cause?

To what danger does the magnetization of ships expose them?

When an iron rod touches one pole of a magnet and is magnetized by induction, is the same kind of polarity as that with which it is in contact carried to its remote end, or does the opposite kind of pole appear there?

Note any instance that occurs to you of an iron or steel magnet which is apparently not due to induction. Keep it in mind, and see whether it remains an exception in the light of fuller knowledge.

## MAGNETIC FIELD: FORCE LINES

**225.** The "dipping needle" (see Ex. 144) is pulled into the line of the earth's full magnetic force, and indicates its direction. Iron filings can be employed to render us a similar service, in discovering the direction of other magnetic force; for they are magnetized on the spot under the influence of a larger magnet, and will align themselves into curved rows in response to the attractions and repulsions then exercised, if the conditions are favorable (Ex. 151). In fact, the filings give us further information about the relative strength of the action at different places, by the thicker or more open clusters that they form. It should be remembered, however, that the filings are really affected by the earth, as well as by other magnets. Whether the effects due to the earth are to be neglected or taken account of in such cases is a matter for practical judgment. What is your decision about it?

After exploring the region round any magnet according to this plan, we find it penetrated everywhere by magnetic influences that lurk in it, as it were, and are ready to become visible through their effects, whenever iron or steel is given them to act upon. The region in which this state of affairs exists is referred to as the **field** of the magnet. In the same terms, there is another field round the earth, ready to exhibit itself as weight, wherever a mass is present (see § 172). The important practical difference between weight field and magnetic field is that the latter appears limited to affecting magnets, while the former acts measurably upon all "substances." The lines delineated by iron filings reveal the directions of the force in a magnetic field; they are the **force lines** of the field,

which is stronger where they are thickly drawn together, weaker where they are more widely spaced.

## CURRENT MAGNETS

**226.** The daily contacts with telephones, telegraphs, and electric lighting, as well as the general use of electric power in propelling cars, have given a certain familiarity to some aspects of the phenomena connected with electric currents. Dynamos and batteries in various forms are recognized as sources of electrical action; the conducting wires seem essential as a channel for conveying it from place to place; and its known results are related closely to our ideas of work or energy (see § 140). The further consideration of such electrical phenomena is the main purpose of the remaining chapters; and among them the magnetic properties of electric currents will first claim our attention.

Electric currents are not streams of anything material like flowing water; their presence or absence is not always directly visible, although they are often betrayed by light and heat in such contrivances as arc-lights or glow-lamps. But the magnetic properties that accompany them in every case are one ready resource to detect them. For example, a straight copper wire is surrounded by a magnetic field whenever an electric current is passing along it (Ex. 152). Iron filings give evidence of force lines running as closed circles concentric with the cross-section of the wire, their planes being perpendicular to its length. And a suspended magnet, if favorably placed, does what it can to indicate the circular force lines by turning its magnetic axis toward a position at right angles to the wire.

But metals are not the only conductors for these currents; they are carried through some liquids, and the same magnetic properties are found to be present round a liquid conductor as round a metallic one, even where the former is a solution containing nothing classed as metal (Ex. 153). This experiment is further instructive because it helps to fix the idea that an electric current maintained by a battery forms an entire circuit, completed through the liquid of the battery itself. Beginning anywhere, we can trace the current by its magnetic action all the way round to our starting-point.

**227**. No magnetic poles can be located in circumstances like these; the force lines are parallel circles, and do not converge upon points or limited areas. Moreover, the action upon the poles of a bar magnet is reversed by interchanging the connections of the conductor with the terminals of the battery or dynamo that keeps the current circulating (Ex.). And no decisive test has been discovered, to tell which way the current flows in either case; we can only say it flows in the *other* direction on reversing it. So, in order that we may know what to expect under given conditions, and connect current magnets definitely with the other types, it has been found desirable to establish two items of agreement — or conventions: —

(1) The direction (or the positive direction) of a magnetic force line is that toward which a north pole points or moves. Thus the direction of the earth's force lines is toward the magnetic pole situated in the northern hemisphere; for a bar magnet, the force lines proceed from its north pole through the air to its south pole.

(2) The direction (or the positive direction) of an

electric current shall be accepted as standing to the direction of its force lines in the relation of *C* (Fig. 89) to *FL*. The head of a right-handed screw is turned round in the direction corresponding to the arrows *FL*, when its point moves forward in the direction *C*, as the screw enters a piece of wood.

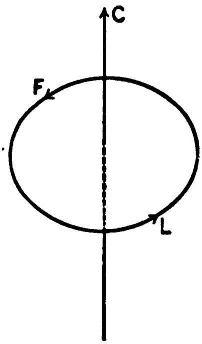


Fig. 89.

Examine such forms of battery as are accessible, that contain zinc with copper or carbon, and verify that the direction of the electric current specified here by the "right-handed screw" relation is from copper (or carbon) to zinc, outside the battery, through a conductor connecting its terminals.

ELECTROMAGNETS

**228.** Each part of the straight wire *AB* (Fig. 90), that carries a current *C*, has its group of circular force lines 1, 2, 3, etc., seen as straight lines when viewed edgewise in the diagram. If the wire be bent into the form *A′B′*, the force lines will be crowded together on the concave side, spread apart on the convex side. And if *A′B′* is thus made into a complete circle, we should look for stronger magnetic force near its centre, because the force lines are brought together there (Ex. 154). With such a coil (especially if made up of sev-

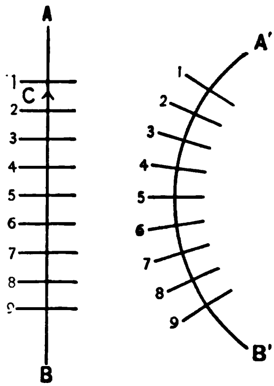


Fig. 90.

eral complete circles) suspended so as to turn freely round a vertical axis, the proof can be added that a current magnet "sets" in the earth's field. The magnetic axis of what we may call an *equivalent* bar magnet is perpendicular to the plane of the circle.

Satisfy yourself that Fig. 89 (§ 227) shows the actual relations of direction, if the *current* circulates as indicated by the arrows *FL*, provided that the *north pole* of the equivalent bar magnet is taken at *C*.

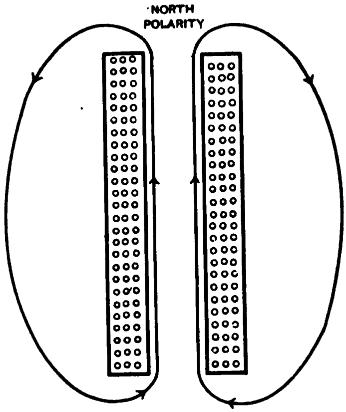

Fig. 91.

According to the evidence presented thus far, a coil or "spool" of wire is a magnet so long as it is carrying an electric current. It manifests *polarity*, but has no recognizable poles; its force lines are closed loops, linked with the circles of the coil, running nearly parallel along the axis of the hollow cylinder upon which the wire is wound, and spreading like a sheaf into the air at the ends of the spool (Fig. 91; Ex. 155).

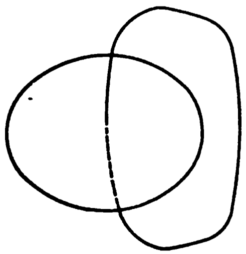
Fig. 92.

Put arrowheads upon the links (Fig. 92) to indicate corresponding directions of a current and one of its force lines.

The action of a current magnet upon iron filings proves its power to magnetize them by induction; and further strong effects

of this kind are produced when an iron "core" occupies the axis of the coil. Note two consequences of introducing the iron: —

(1) The polarity is changed in strength, but not in character; the north pole is at the same end of the coil as before. This registers the fact that inducing action takes place through a "core of air," carrying north polarity in the same direction as it does through a core of iron, but not so freely (see § 224).

(2) Poles can now be identified near the ends of the iron core, as in other cases where force lines come to the boundary between iron (or steel) and air.

A current magnet provided with an iron core constitutes the usual form of an **electromagnet**, although, as we have seen, the iron is no essential part of the arrangement, except for strength; electromagnets far exceed permanent steel magnets in the forces that they exert.

The mutual attractions and repulsions of coils or wires carrying currents agree in detail with those that are found on substituting equivalent bar magnets, but a current magnet at a red heat retains its power of exerting magnetic force and responding to it (Ex. 156; see Ex. 148).

The fact that conductors are magnets while conveying currents was discovered by Oersted, and the idea was worked out completely by Ampère (Ref. 44).

Have you any evidence which is open to the interpretation that magnetic force prefers a track through iron to one of the same length through air, leaving the latter and seeking the former? Do you see any other explanation of the same facts?

Examine any electromagnet that you find in use, with regard to the proportion of path through iron offered to its

inducing influence. Why is the iron preferable to air? In holding a piece of iron in contact with both its ends, does a horseshoe magnet (of any type) exert practically twice the force that either end separately would exercise (Ex.)?

Notice the construction of an electric bell; especially the device for alternately attracting and releasing the piece that carries the hammer.

**229.** In the common form of electric telegraph, the "dot and dash" signals interpreted as letters are caused by the intermittent action of an electromagnet. A key at the station from which the message is sent permits the conducting circuit between two offices to be interrupted and completed at will; and with every new start of the current, a movable piece of iron or steel, the "armature," is snapped into place with a sharp click by the electromagnet at the receiving end (Ref. 45). The spacing and grouping of these signals carry their meaning to the operator's ear; or the fragments of current may be made to record themselves as visible dots (short marks) and dashes (longer marks) upon a paper ribbon.

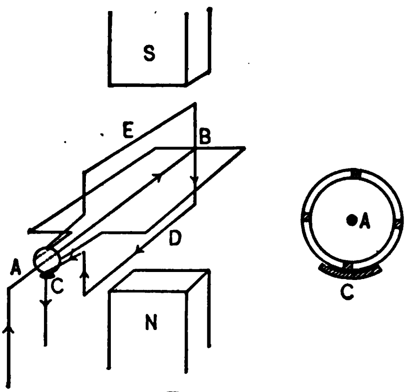

Fig. 93.

Current magnets (without iron core) and electromagnets (with iron core) enter prominently into electric motors, of which one type is represented in the annexed diagram (Fig. 93). This is to be understood

as a skeleton outline, simplified to the utmost in order that the essential action may become apparent. The study of a model, or of the construction in a real motor, is a necessary supplement to the discussion of the text.

The north pole of a powerful electromagnet is shown at *N*, and the south pole vertically above it at *S*. Electric current is supplied at *A*, its (conventional) direction being indicated by the arrow; it passes along the horizontal conductor ***AB*** to *B*, and completes its course as marked to *C*, where it leaves the motor. There are four such rectangular frames of copper wire meeting on the common axis ***AB***, about which they can revolve as one rigid piece; and each in turn becomes the carrier of the current from ***B*** back to *C*, as its nearer end makes sliding contact with the fixed conductor at *C*. The smaller diagram shows an enlargement of the revolving disk at *A*, with the fixed piece *C*; the conductors are shaded, the rest of the disk being non-conducting.

In the position as drawn, the rectangle *ABDC* is a magnet, while the three others are idle. The magnetic axis of the equivalent bar magnet is horizontal and perpendicular to *AB*. In which direction would the frame turn about *AB* under the repulsion and attraction of *N* and *S*? The arc *C* might be made long enough to render this action effective through a considerable angle; and then it would be repeated with the next rectangle, after a pause during which no conducting path is offered to the current. In an actual motor, there is an advantage in employing a larger number of frames; and it is contrived that a pair like *ABE* and *ABDC* shall be active at the same time. Satisfy yourself on both these points.

In speaking thus briefly of the telegraph and the motor,

each of which is a study by itself at its modern stage of development, sufficient to occupy an electrical engineer in his difficult profession, it is not intended to dismiss these matters with a few sentences, but only to open up a track for further thought and reading.

## GALVANOMETERS

**230.** In the motor that we have been describing, the frames mounted on the axis *AB* (Fig. 93) have no tendency to turn unless a current is passing along their wires, if their weights are properly balanced; it is evident, therefore, how such a motor could be used to indicate the presence or absence of electric current. And by arranging the frames so that they would turn very easily, the instrument might be made to detect traces of magnetic property in *ABDC*; in other words, to give evidence of what is called a *weak* current there, since it is natural to regard the magnitude of the magnetic effects as corresponding to the strength of the current that causes them. This is, in fact, the essential idea of the instrument employed in many forms to show when electric currents are passing along its conducting wire, and known as a **galvanometer.** Besides the temporary current magnet, a galvanometer usually contains a permanent magnet of hardened steel, instead of an electromagnet; and, because the attractions and repulsions between two magnets are mutual, either the permanent magnet may be movable and the coil of wire fixed, or *vice versa* (Ex. 157). In the diagram (Fig. 94), the permanent magnet *NS* is mounted like a compass needle, while the coil *AB* is fixed; and it is left as an exercise to adapt the following statements to the other case.

Like any other magnet suspended so as to turn horizontally, *NS* will have its magnetic axis drawn into the magnetic meridian, supposing the earth alone to act upon it; and that axis can be made to lie along a diameter of the coil by shifting the direction of the latter until its end faces are parallel to the magnetic north and south line. If *AB* then becomes a magnet by virtue of a current circulating in it, *NS* will swing aside until it reaches a position of balance, where earth and coil have equal and opposite moments to turn it round the pivot at *P* (see § 164, end).

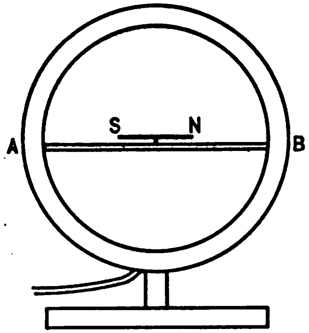


FIG. 94.

The two forces *F* (Fig. 95) exerted upon *NS* by the earth are equal, opposite, and parallel to the magnetic meridian *MM* (see § 223, end). The two forces $F_1$ exerted by the magnet *AB* are nearly parallel to the axis of the coil, as shown by the iron filings (see Ex. 154); and they are equal and opposite because the whole arrangement is symmetrical. Consequently, each force $F_1$ is nearly perpendicular to *MM*, after adjusting the axis of the coil to the magnetic east-west line. The moment of the two

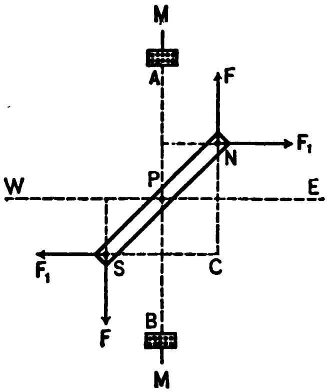


FIG. 95.

forces $F$ is $F \times SC$; and that of the forces $F_1$ is $F_1 \times CN$. If these moments are equal at the position of balance,—

$$F_1 \times CN = F \times SC; \quad \frac{F_1}{F} = \frac{SC}{CN}; \quad F_1 = F \times \frac{SC}{CN}. \quad (33)$$

As the magnet swings farther away from the magnetic meridian, $CN$ shortens and $SC$ lengthens, until a very great force, $F_1$, is necessary to hold the magnet at a position where $NS$ is nearly in the direction $EW$.

Since the force ($F$) due to the earth's action at a definite place, and upon a particular magnet, may be regarded as constant for our purposes, the comparative magnitudes of the magnetic forces ($F_1$) exerted by the coil at different positions of balance is shown by the corresponding values of the ratio $\frac{SC}{CN}$. Where the scale past which the ends of the magnet $NS$ move has intervals numbered by degrees, as in the compass, the angles such as $NPM$ are read directly. The ratio $\frac{SC}{CN}$ can then be obtained by laying off the angles with a protractor, drawing a circle with any radius round $P$ as a centre, and measuring the distances corresponding to $SC$ and $CN$. We shall adopt the ratios $\frac{SC}{CN}$ as a comparative measure of electric currents circulating round the same coil at the same place, the axis of the coil being always perpendicular to the magnetic meridian. This is the beginning of a plan for measuring electric currents by their magnetic effects.

Would exchanging the magnet $NS$ for another affect the results?

Can the magnet $NS$ be replaced by a second current magnet?

# CHAPTER XVII

## SOURCES OF ELECTRIC CURRENT. EFFECTS IN CONDUCTING CHANNELS. OHM'S LAW. ELECTRICAL ENERGY

**231.** Electric currents can be excited and maintained in a number of ways; but the main sources of them, to which we shall confine ourselves, are two: (1) chemical action such as goes on in batteries of various types; (2) mechanical work, applied to a dynamo. The chemical processes occurring in batteries would on the whole always be sources of heat in circumstances where electric currents could not be developed. The batteries become sources of electric currents, in proportion as the energy is diverted that way from the form it would otherwise take as heat; the chemical solution of zinc is a typical instance, where electrical energy can be made to appear, instead of heat; and it is in fact utilized in several common forms of battery (Ref. 46). The chemical activities of materials in each other's presence have to be accepted as properties with which they are endowed; we can only discover such properties and make them serviceable. The energy available as heat or in other forms when a given number of grams-weight enter into combination is likewise beyond control; but the dynamo is more directly a human contrivance, in the sense that the conditions in it can be varied, and the effectiveness of it improved in the light

of experience. We shall discuss first the circumstances which favor the conversion of work into energy connected with electric currents.

## INDUCED CURRENTS

**232.** When the ends of a coil *C* (Fig. 96) are joined by a wire *W*, so as to form a complete conducting channel, an electric current can be excited in it by introducing a bar magnet *NS* along its axis, and by withdrawing the magnet, without connecting the coil to a battery, or even touching it (Ex. 158). Such currents are transient; they are not observed so long as the magnet is held in one position, but only while it is moving. They are known as **induced currents** (or induction currents), and their existence was discovered by Faraday (Ref. 47). Study the directions of these currents with reference to (1) the end of the coil at which the magnet enters, (2) the pole of the magnet which enters first, and (3) the comparative effect of introducing the magnet and withdrawing it. In every case it will be found that the induced currents develop such polarity of the coil as to repel the magnet while it is advancing, and to attract it while retreating. That is, work must be done to move the magnet against the opposition caused by the currents, in addition to the work connected with its weight. The electric energy of the induced currents is the equivalent of extra work thus done.

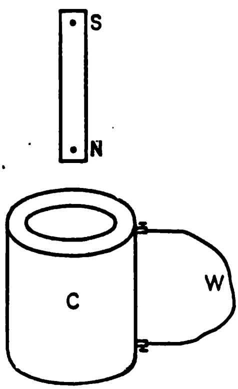

FIG. 96.

Convince yourself that all these effects are producible if the magnet is stationary and the coil is moved.

The action between bar magnet and coil has been chosen as a typical instance, but induced currents are observable when a current magnet, an electromagnet, or the earth replaces the bar magnet, provided the conditions are parallel in other respects (Ex. 159). Electromagnets are particularly convenient in exciting induced currents, because they can be left in place within the coil where an induced current is to circulate. Their magnetic properties come and go at the closing or opening of a key; and this is practically the same as bringing up a magnet from a distance, or removing it. The essential fact presented by these experiments seems to be that induced currents will circulate in a closed conducting channel, whenever the magnetic field within its boundaries is changed in strength. The induced current excited in a given coil will be stronger: (1) when a greater change of field is brought about in the same time; (2) when equal changes of field take place more quickly. What evidence for these two statements do you find in the phenomena?

A straight electromagnet is used to excite induction currents in a coil surrounding it on the same axis. What motions of a bar magnet would be equivalent to a reversal of the current *in the electromagnet?* Such arrangement of two concentric coils and an iron core is frequently put together under the name of **induction coil.** The inner coil (of the electromagnet) and the outer one (in which induction currents are caused) are then called the primary and the secondary coil, respectively. What advantage do you see in using very soft iron for the core of an induction coil?

What motions of a bar magnet would produce induction currents of the same direction as those caused by turning a coil once completely round in the earth's magnetic field? Why does moving a coil "parallel to itself" in the earth's field excite no induction currents?

Point out how the attraction and repulsion of a copper disk by an electromagnet differ from other magnetic forces previously observed (Ex. 160). Show that the temporary magnetic properties in the copper disk fit the supposition that they are due to induction currents in it.

**233.** The electric currents furnished by a dynamo are induction currents, originating in a coil of wire, or armature, which revolves relatively to the field of a powerful electromagnet. The mechanical work required to do this being supplied by steam or gas engines, water-wheels, or windmills, a considerable percentage of it becomes available as electrical energy, after deducting for losses by friction, etc.

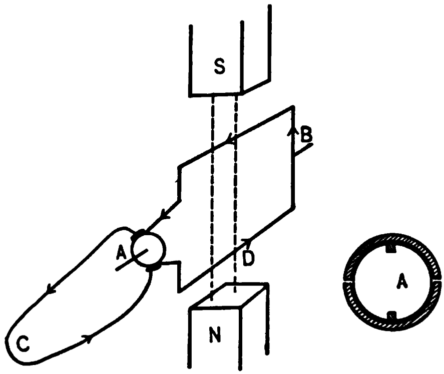

FIG. 97.

Do you recognize both kinetic and potential energy in the sources of work named?

The poles $N$ and $S$ (Fig. 97) are supposed to be those of a strong electromagnet, the direction of the force lines being vertically upward as indicated. $ABD$ represents a frame of copper wire, capable of turning

round a horizontal axis $AB$, and each of its ends at $A$ rubs on a contact with the conducting loop or circuit $C$, so that frame and loop together form one closed conducting channel during the greater part of a revolution. The contacts are shown on a larger scale in the figure at the right. In the position drawn, the ends of the frame make contact at $A$, its plane is vertical, and it includes none of the field within its boundary, because the force lines are parallel to its plane.

In which direction must the frame be turned about $AB$, in order that the induced current may circulate as shown by the arrows (see § 232)? Suppose that the frame has turned in that direction through 180°, so that $D$ is now uppermost, and notice that the induced current will still be *forward* toward $A$ in the upper length of wire. Consequently, the induced current enters the loop $C$ at the *upper* contact always, and circulates in the same direction through $C$ during the whole time of contact at $A$. At which position of the frame will the induced current become zero; that is, change sign (or direction)?

We have before us here a simplified outline of the dynamo in one form, when designed to furnish "continuous current" (*i.e.* current of the same direction) in the circuit represented at $C$, by passing the "alternating" currents of the armature $ABD$ through the "commutator" (or sliding contacts on the disk $A$). In this case, again, models and examples of actual construction must be brought to bear, as well as diagrams and discussion of printed statements. It is instructive to compare this scheme with that of Fig. 93 (§ 229), and notice the *reciprocal* relation between the two. In the former case, electric current is furnished and work is obtained; in the

present instance, work is supplied and electric current is the result. The one transformation of energy undoes the other. Describe the general effect of increasing the number of frames, such as *ABD* (Fig. 97), and adjusting the sliding contacts so that each frame is near its vertical position when it is connected with the circuit *C*. How does the current-strength depend upon the rate of turning?

## ELECTROMOTIVE FORCE: ELECTRIC RESISTANCE

**234.** Every experience with any form of dynamo or electric battery shows it to be the seat of an influence that is ready to set an electric current in circulation, when a conducting channel or circuit is provided. A convenient descriptive name for such an influence is **electromotive force**, and we shall follow ordinary usage in accepting it. A word of caution is necessary at once, however, about the word "force" as employed here; it must be taken in its broader sense of agency or influence, and not in its more special meaning of *mechanical* force that acts upon masses, and is measurable in grams-weight (see § 25, end). With this understanding, the term electromotive force can be properly translated by "influence moving electric currents"; but it is not measurable in grams-weight, because no material having grams of mass moves in electric currents.

A definite source of electromotive force, like a Daniell cell, or a storage cell, yields widely different effects according to the material offered as a path for the current, after equalizing conditions in all other respects (Ex. 161). First, there is a distinction, clear enough in ordinary circumstances, between substances like air, glass, dry

wood, hard rubber, which are classed as **non-conductors**, or **insulators**, and **conductors** like the metals. But, secondly, marked differences appear among the conductors themselves, and render it practically necessary to make measured comparison among materials as paths for electric currents. That property in a substance which prevents the development of an electric current in it, is appropriately termed its **electric resistance**; so that electromotive force and this resistance are conflicting elements connected with any circuit, whose relative magnitude is expressed by the strength of current developed in that particular channel. Measurement has been applied to all three factors involved in this adjustment, giving us three *quantities* to consider: (1) electromotive force; (2) electric resistance; (3) current-strength. We shall aim to reach a definite statement of the connection among these quantities for any circuit, having first described the standard adopted for each one, beginning with resistance.

**235.** If a conductor consists of homogeneous material, its electric resistance is affected chiefly by its length and the area of its cross-section, and to a smaller extent by its temperature. When the conductor has the form of a wire, its cross-section may be regarded as uniform in area everywhere, and its resistance increases in direct proportion to its length. If the length of the wire is multiplied by joining a number of meters end to end, whatever opposition there is to the passage of current through one meter of it is repeated in every other. As regards area of cross-section, on the contrary, increasing that in any ratio *diminishes* the resistance in the same ratio. The inference is that the current distributes itself uniformly, and avails itself equally of every equal area in the cross-section, by

following as many parallel and *simultaneous* channels, each 1 □ mm. in area, as there are square millimeters of cross-section in the wire. Other things remaining unchanged, the total current would then be multiplied to correspond, when the area is increased, and gives more parallel channels; or the resistance of the whole wire would be divided in the same ratio, which agrees with the observed fact.

When a conductor is heated or cooled, its electric resistance is usually changed, but the change is not expressible in any simple rule. Carbon and conducting solutions diminish in resistance as their temperature is raised; the opposite effect is produced generally in metals, but some alloys have very nearly constant resistance through a large range of temperature.

The international standard of resistance that has been adopted takes account of the effects due to (1) material, (2) temperature, (3) length, and (4) area of cross-section. It is specified as the resistance offered at 0° by a cylindrical column of mercury, 106.3 cm. long, and weighing 14.4521 gr.-wt. The last item is only an indirect way of requiring the cross-section to be 1 □ mm. in area, and is chosen because the necessary weighing can be executed with greater precision than the measurement of a small area. This standard with which the resistances of conductors are compared has been named **one ohm**; electric resistances are "measured in ohms." The resistances of a few materials are given in the table; they are reckoned for a uniform column 1 meter long, and 1 □ mm. in area of cross-section, as a convenient starting-point in calculating resistances for other dimensions. The numbers are not accurate enough to require that the temperature should be known.

ELECTRIC RESISTANCE (Ohms to 1 meter; 1 □ mm. area)

| | | | |
|---|---|---|---|
| Silver . . . . . | 0.014 | Lead . . . . . | 0.188 |
| Copper . . . . . | 0.015 | German silver . . | 0.200 |
| Platinum . . . . | 0.087 | Mercury . . . . | 0.944 |
| Iron . . . . . . | 0.093 | Carbon . . . . | 40 to 100 |

Expressed on the same scale, the resistance of liquids used in batteries would be measured by tens or hundreds of thousands. In the table, the metal with the smallest resistance is the best conductor for electric currents ; and the order here matches pretty well that in the table of conducting power for heat (see § 157). There is in this fact some suggestion that the two processes of conduction are to a certain extent similar.

## ELECTRIC CURRENT-STRENGTH

**236.** Turning next to current-strength, we find this measured daily in electric light and power stations, as well as in physical laboratories, through the magnetic properties of currents, as suggested in § 230. But the legal standard for measuring electric currents is expressed in terms of the chemical results that accompany their passage through certain solutions ; and in leading up to a description of that standard, it becomes necessary to give some brief account of such chemical effects in the conducting channel, which have always been prominent phenomena there.

In the early history of electric currents, chemical action was the single source available to excite them ; and chem-

ical decomposition produced by their means soon led to important discoveries of new elements (Ref. 48). In the Daniell cell, the eating away of the zinc, and the separation of copper from a solution containing it, go on within the same circuit (Ex.); and the latter result is only one example among many, where thin metallic layers are gradually deposited upon objects in the process of electro-plating. With the aid of strong currents from a dynamo, it has grown to be a regular metallurgical method on a large scale, to gain metal from its ore in this way. Chemical changes are brought about in a storage battery by the "charging current," which are undone when the battery is itself used as a source of current (Ex. 162).

**237.** If an electric current passes between two copper plates through a solution of copper sulphate, it is found that one plate gains in weight while the other loses (Ex.); and, apart from disturbing influences, gain and loss are equal. Suppose that a galvanometer forms part of the same circuit, and indicates the magnetic properties of the same current, which, as we know, is equally strong at all places in its closed loop. In a general way, anybody would be likely to expect that copper will be deposited faster when the magnetic forces are greater; but Faraday made out a definite and remarkable connection between the two phenomena, which are so unlike and unrelated on the surface. He found that the *magnetic field* round the current is always proportional to the *rate* at which the copper is deposited (or eaten away). If that rate is doubled, or halved, or changed in any ratio, the strength of the magnetic field is changed in the same ratio. Note that the *angle* made with the magnetic meridian by the

magnet of the galvanometer at the position of balance does not change in the same ratio as the field; but, with the *same magnet*, the forces $F_1$ are proportional to field-strength, and measure it comparatively, as the weight of the *same body* is proportional to $g$ (see §§ 176, 223, 230).

Faraday then proceeded to determine the corresponding weights of silver, copper, etc., that are deposited by the same current in the same length of time, and completed a scheme for this chemical measurement, which is equivalent to the measure in terms of magnetic properties. It happens that the deposit of silver is experimentally more reliable than that of copper, and accordingly it has been chosen in stating the standard of current-strength. Other electric currents are compared with that which deposits 4.025 gr.-wt. of silver an hour; this is named **one ampere**, and electric currents are "measured in amperes." One ampere of current deposits about 1.2 gr.-wt. of copper an hour. What rates of deposit measure 3.4 amperes?

It will be noticed that neither the ohm nor the ampere is specified in terms of convenient whole numbers, but they involve one or more decimals in the length and weight given. The numerical difficulty thus introduced is only apparent, however; these units are parts of a really simple plan for electrical measurements, but the reasons why it is simple cannot be explained here.

The weighed deposit of silver can evidently determine only the average value of the current during a relatively long interval; and, although the accumulated chemical action is excellent for standardizing, the various forms of galvanometer are indispensable, because they indicate at once the momentary strength of a current, and enable us to follow its changes as they occur.

## OHM'S LAW

**238.** In comparing the electromotive forces of two circuits, we should naturally judge that one to be larger which proved able to maintain a stronger current, if the resistances of the circuits were equal. Or, if the currents were equal, and not the resistances, we should recognize that electromotive force as larger which established an equal current in the face of greater resistance. Both these aspects of the relation are included in one statement, if the *product* of current-strength ($C$) and resistance ($R$) is made the measure of electromotive force ($E$). For, in symbols, if $E = CR$, $E$ increases and diminishes directly according to the magnitude of $C$, so long as $R$ retains the same value; and directly according to the magnitude of $R$, so long as $C$ retains the same value.

This plan is the one adopted; so that an electromotive force is expressed numerically by multiplying together the number of amperes in the current which it causes, and the number of ohms in the resistance against whose opposition the current is made to circulate. The agreement to measure electromotive force this way fixes the standard for it without further choice, as being the influence active when one ampere of current is maintained in one ohm of resistance, since we must have $E = 1$, if both $C = 1$ and $R = 1$, when $E = CR$. The standard of electromotive force thus established is named **one volt**, and electromotive forces are "measured in volts"; the electromotive force in a source of current is its **voltage**. One type of cell can be put together, that furnishes practically an electromotive force of one volt, but it is not in common use. Speaking in terms of a more familiar combination, the Daniell cell will

help us to realize the magnitude of the unit here; its electromotive force is about 1.05 volts.

Where opposing influences are of the same kind, a compromise between them is represented mathematically by subtraction, as in the case of weight and friction, or weight and the pull of a spring (see § 25). But electromotive force and electric resistance are not quantities of the same kind; and their conflict, whose outcome is registered in the strength of the current established (see § 234, end), takes mathematical form as division, since $\frac{E}{R} = C$ follows from $E = CR$. We have encountered a similar relation elsewhere, when one quantity is measured by the product of two others. Thus, if $H$ calories of heat are transferred to $W$ gr.-wt. of water, the *rise* in temperature ($T$) is given as $\frac{H}{W} = T$; the rise in temperature is the compromise between the "heating effect" of $H$ calories, and the "cooling effect" of spreading them through a body of water. So the positive action of weight is *divided* by the passive resistance of inertia, in order to determine the speed added in a second to a falling body; $\frac{W}{M} = Cg$ follows from $W = CMg$ (see § 177, end), and we can make the proportional factor $C = 1$ by a proper choice of units.

**239.** We have now obtained the equation, $E = CR$, to represent the condition of adjustment in a single closed loop of circuit containing one source of electromotive force that applies $E$ volts. The current of $C$ amperes *circulates;* that is, its strength everywhere round the loop has the same value. And $R$ ohms of resistance includes the whole circuit: liquids and plates of a cell, or armature wires of

a dynamo (internal resistance), as well as the conducting channel outside the cell or dynamo (external resistance). This is the simplest case of the relation discovered and formulated by G. S. Ohm in 1826, and known as **Ohm's Law** (Ref. 49), which is a central principle of electrical science. We shall illustrate somewhat further how it is to be understood in connection with electric circuits, where the elements of a single closed loop are repeated or combined.

It occurs frequently that two sources of electromotive force are contained in one loop (Ex. 163). The question then is, whether each separately would cause current to circulate in the same direction, or in opposite directions. In the first case, the electromotive force (voltage) effective in the circuit is the sum of that in each source; in the second, it is their difference; we are here returning to the addition and subtraction of like quantities. The current actually observed is established in direction by the stronger electromotive force; and the symbol $E$ must now be taken to mean the algebraic sum of the electromotive forces that the circuit includes.

Distinguish the action of an opposing electromotive force in weakening the current that circulates, from the effect of electric resistance. Increasing the resistance makes current weaker indefinitely, but cannot *reverse* it; increase of opposing electromotive force soon turns the balance the other way, and causes current to circulate in the contrary direction. This emphasizes the mathematical distinction between cutting down a result by division and by subtraction, which was explained in the preceding section.

The idea of summing electromotive forces algebraically covers the common case where a number of similar cells

are joined **in series**, or to aid each other in the same circuit; the voltage of one cell is multiplied by the number thus connected.

What quantities belonging to the circuit are changed by adding to the number of cells, besides electromotive force? Compare the consequences of increasing the number of cells from 1 to 10 in these two cases: —

(1) External resistance (outside the battery) 20 ohms; internal resistance of each cell 0.5 ohm; voltage of each cell 1.6 volts.

(2) External resistance 5 ohms; internal resistance of each cell 8 ohms; voltage of each cell 1.1 volts.

One great advantage of storage cells is that they unite high voltage (over 2 volts) with small internal resistance (perhaps less than 0.1 of an ohm). What is the practical result as regards current-strength, of multiplying the number of cells in a circuit under these conditions?

Of how great relative importance is internal resistance of batteries on long telegraph lines?

## TRANSFORMATIONS OF ELECTRIC ENERGY

**240.** The batteries in daily use consist of two different solids in contact with the same liquid or with different liquids. The presence of two substances that are acted upon more and less by the liquid seems an essential feature in these sources of electromotive force. The solids are zinc and carbon in the Grenet and the Leclanché cells, zinc and copper in the Daniell and the gravity cells, lead at two stages of oxidation in the storage cell. Which surface is acted on less in each type of cell among the first four?

The voltage of such a combination depends upon the

substances in contact, but not upon the area of the plates, nor upon their distance apart (Ex. 164). The effective surfaces may be changed, though, as a consequence of the current passing through the cell, and the electromotive force be thus altered. This is notably observable if gas is liberated, and covers one surface (Ex. 165); the voltage is reduced by such action, which is called **polarization.** A like effect can be produced in the circuit outside the battery, on immersing two plates of the same substance in a liquid, and causing current to pass between them (Ex. 166); an electromotive force opposing the original current is excited, and may bring matters to a standstill. The decompositions brought about in this way draw upon the energy of the original source of current, and, in the case of storage batteries, make it available for future use; they are "storage-of-energy batteries."

A similar tendency in a current to excite opposition to its own circulation, and to reduce its own strength, is seen also in the electric motor (Ex. 167). The current is weaker when the armature has been set to turning rapidly, than it is when the armature is held at rest, although the *resistance* of the circuit is the same in either case. A part of the energy leaves the electrical form at the motor, and assumes again the mechanical form which it abandoned at the dynamo. In the storage battery the change is between electrical forms of energy and the chemical forms. Notice that an *opposing electromotive force* is a condition attendant upon the transformation of energy in both instances. These automatic changes of electrical energy into other forms are the foundation of its great convenience in carrying power (see § 171) from a distant source to the place where it is turned to account.

A third interesting instance where energy is not electrical as received and delivered, but is changed into electrical form for transmission, is found in the telephone. Sound-energy is carried by the air from the person speaking, as far as the diaphragm *D* (Fig. 98) of the "transmitter," which is set in motion. Though the movements of *D* are imperceptible, they are sufficient to vary the pressure at the contacts *T* just behind it, and to alter the resistance in the circuit including the "dry battery" *B*, and the primary wire (see § 232) of the induction coil *C*.

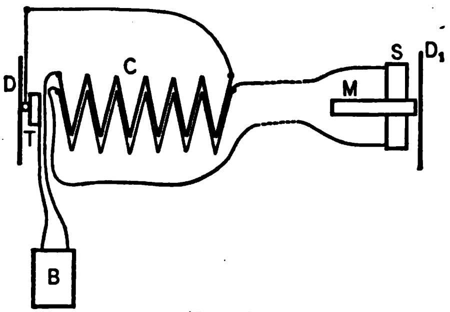


FIG. 98.

The alterations of resistance bring about changes in current-strength, and therefore of magnetic field within the boundaries of the secondary coil in *C*. The induction currents that are the response to these changes of field find a complete channel through the line wire and the spool *S* at the receiving end. The varying magnetic properties of the spool modify the field of the permanent magnet *M*, and attract the iron diaphragm $D_1$ more or less strongly. The fluctuations of position in the diaphragm *D* are thus followed faithfully by those of $D_1$, which restores to the air there a fair copy of the original sound-energy; the "voice is heard" at $D_1$. The transmitter is essentially a small-scale dynamo, and the receiving telephone a motor.

**241.** We speak ordinarily of induced *currents*, and the phrase has its proper meaning; but behind the currents

there are, of course, induced electromotive forces, and the conditions mentioned in § 232, (1) and (2), determine these rather than the currents (Ex. 168). What strength of current will develop depends upon the material provided for the conducting channel.

The same induced electromotive force is repeated upon every new loop of a secondary coil about the magnetic field of its primary coil, and the influence acting upon one loop is therefore multiplied by the number of such circles or loops that are made. But the induced currents of the usual induction coil are very weak, though its secondary circuit makes many hundreds of turns round the primary coil (Ex. 169); and it may be asked how this comes about if the electromotive force is so large. The answer is readily given, so soon as we consider definitely in what ratio the resistance of a given wire is changed, as it is drawn down into a greater length of a finer size, while it retains practically the same volume. The original resistance is multiplied once by the ratio of the new *length* to the old; and once again by the same ratio, because the *area* of cross-section is reduced in proportion as the length increases. Consequently, the induced electromotive force increases (under favorable conditions) nearly according to the first power of the length, since more loops can be made with the longer wire; but the resistance increases as the second power of the length, and taking both these elements into account, we can see why the current is reduced by making the wire longer and finer.

In what ratio does the current-strength change, on the suppositions made above? Show that substituting a thicker wire of the same total volume can multiply the current, though it diminishes the electromotive force. This is

the central idea of the **transformer**, as used in *reducing* voltage.

Several matters connected with currents of varying strength have been introduced into this section and the one preceding, because they aid in obtaining a view of important conditions under which electromotive forces appear in circuits. But it should be said explicitly that Ohm's Law in the form $E = CR$ applies to constant or "steady" currents only; its extension to varying currents is far beyond the limits set for us.

## BRANCHED CIRCUITS

**242.** While an electric current is circulating in a conductor, an electromotive force is active between any two points of the circuit, which becomes greater as those points are moved farther apart (Ex. 170). And, if such an electromotive force is measured by compensating it, we find that the expression, $E = CR$, holds good for any part of the circuit, as well as for the complete loop, if the values of all three quantities are those for the part under consideration (Ex. 171). The diagram (Fig. 99) represents the plan realized in the last experiment.

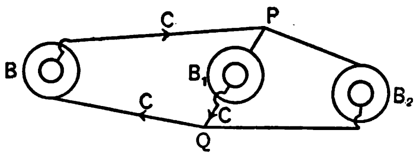


Fig. 99.

The battery $B$, of known voltage $E$, gives the current $C$ its direction, the smaller known voltage, $E_1$ at $B_1$, being overpowered. Assuming also that the resistance $R$ of the circuit $BPB_1Q$ is known, we can calculate $C$ by the relation, $C = \frac{E - E_1}{R}$. The compensating battery $B_2$, of known

voltage $E_2$, is connected at $P$ and $Q$, the resistance of the part $PB_1Q$ being $R_1$; and when the adjustment has been made, $E_2$ is equal and opposite to the electromotive force caused *by* $B$ between $P$ and $Q$; let this be denoted by $E_{PQ}$. The result shows that $E_2 = E_1 + CR_1$, or $E_2 - E_1 = CR_1$, or $E_{PQ} - E_1 = CR_1$; and in the last form, the first member of the equation, representing an algebraic sum of electromotive forces for $PB_1Q$, is measured by the product of the resistance and the current-strength belonging to that part of the circuit. That is, Ohm's Law applies to any part of a circuit in which a steady current is circulating; for the reverse electromotive force $E_1$ may have any origin, without changing the result. One corollary to this reasoning is that a larger fraction of the electromotive force of a battery becomes available for the *external* part of the circuit, in proportion as the resistance of the battery itself is small.

**243.** Circuits are often branched or divided, so that the current is shared between two or more channels in some parts, and reunited in others. The method of reckoning resistance, current-strength, and electromotive force in simple cases of that sort is next to be explained.

Let $AB$ (Fig. 100) represent any circular cross-section of a wire through which an electric current $C$ circulates. Then one-fourth of $C$ goes across the quadrant marked 1, and three-fourths of $C$ across the remaining quadrants, all

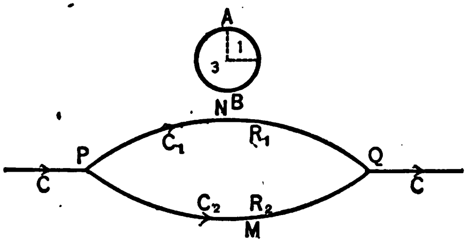


FIG. 100.

along the wire (see § 235); and, if such a single wire joining $P$ and $Q$ were divided lengthwise into two strips, $PNQ$ and $PMQ$, having cross-sections 1 and 3, the ratio of the current carried by the former to that carried by the latter would be $\frac{1}{3}$. The resistances would be in the ratio $\frac{3}{1}$, the strips being of equal length and the same material, while their areas of cross-section are in the ratio $\frac{1}{3}$ (see § 235). Hence, in this case the total current would be divided between the two strips in the inverse ratio of their resistances. But this idea can be extended to any two conductors "in parallel" joining two points, although they are of different materials and lengths, by substituting for one of them a wire equivalent as regards resistance, and having the same material and length as the other. For example, let $PNQ$ be a copper wire 500 cm. long and 3 □ mm. in cross-section; $PMQ$ a wire of German silver 375 cm. long and 7 □ mm. in cross-section; and calculate the cross-section area of a German silver wire equivalent to $PNQ$. The resistance must be $(0.015 \times \frac{5}{3}) = 0.025$ ohm (see Table, § 235); and the area $a$, of a German silver wire 375 cm. long that has this resistance, can be calculated from the relation, $0.2 \times \frac{3.75}{a} = 0.025$, giving $a = 30$ □ mm. The ratio of the current in the copper wire to that in the original German silver wire is then $\frac{30}{7}$, because the cross-sections have that ratio when reduced to equivalents in the same material. This is the inverse ratio of the resistances calculated directly from the materials, sizes, and lengths, as direct trial will show.

The result of the last paragraph expressed in symbols is $\frac{C_1}{C_2} = \frac{R_2}{R_1}$ (see Fig. 100); from which we obtain the equa-

tion, $C_1R_1 = C_2R_2$, either member of which gives the electromotive force active between $P$ and $Q$, or $E_{PQ}$ (see § 242). It is sometimes convenient to calculate directly, in terms of $R_1$ and $R_2$, the resistance $R$ of a single conductor in which that electromotive force would develop the current $C = C_1 + C_2$. Such a wire would stand in the same relation to the circuit as the conductors of resistance $R_1$ and $R_2$ "in parallel," and could replace them without changing resistance, current-strength, or distribution of electromotive force. The condition to be fulfilled is $\frac{E_{PQ}}{R} = C = C_1 + C_2$; but $C_1 = \frac{E_{PQ}}{R_1}$, $C_2 = \frac{E_{PQ}}{R_2}$; consequently, cancelling the common factor $E_{PQ}$, we find $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$, or $R = \frac{R_1R_2}{R_1 + R_2}$, for the value required.

Calculate in this way the single resistance equivalent to the copper and the German silver wire in the preceding numerical example, and show why it equals that of a German silver wire 375 cm. long, with a cross-section of (30 + 7) □ mm.

The diagram (Fig. 101) represents the plan of connecting similar cells "abreast" or "in parallel." Notice that the two cells are effectively the same as one larger cell. What effect upon electromotive force and internal resistance has this use of two cells as compared with one of them? In what circumstances would this arrangement offer advantages (see § 239)?

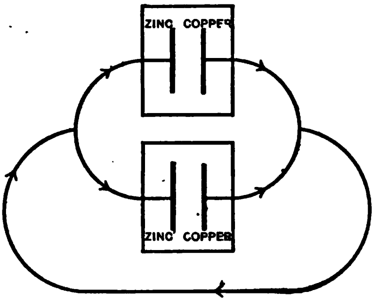

FIG. 101.

## MEASUREMENT OF ELECTRIC ENERGY

**244.** The heating effect upon conductors is a process that continues so long as the electric current is passing through them; therefore it is not quantity of heat that is to be measured, but the number of calories (see § 116, (2)) a second; or, if comparisons of heat-quantity are made, it must be upon the basis of equal times. When temperatures become constant while current is circulating, it does not mean, of course, that the heating has stopped, but that the rate at which heat is gained from electrical energy is equal to that at which heat is lost by conduction, convection, and radiation (see § 114). With a given value of current-strength, this process of heating is intensified in places of greater resistance to the centimeter of length, and less marked where the resistance is smaller. The carbon filament of a glow lamp is made luminously hot by a current of one ampere, whose passage leaves the copper wires in the same circuit cool. The heating is, in fact, so distributed round the circuit that it matches the distribution of resistance; and measurement shows that the quantity of heat supplied in one second at any part of the conductor by the same current is proportional to the resistance there (Ex. 172).

The heating effect in any particular conductor becomes more vigorous when the current circulating in it is strengthened. This we might naturally expect, since the current brings the supply of energy, while the resistance of the conductor only causes the transformation of electrical energy into heat. But the number of calories a second appearing in a given resistance runs up faster than the current-strength does (Ex. 173); it is multiplied by four

on doubling the current, and in general varies according to the *square* of the current-strength. The numerical relation established by accurate measurements proves that a conductor having a resistance of 4.2 ohms changes electrical energy into heat at the rate of 1 calorie a second, when a current of 1 ampere is carried by it. A current of 2 amperes would yield 4 calories a second in the same conductor; one of 3 amperes, 9 calories a second; and so forth. This result is part of the fruit borne by Joule's investigations concerning the transformations of energy (see Ref. 24).

The quantity of heat ($H$) appearing as the equivalent of electrical energy connected with current depends then upon (1) time ($T$), (2) resistance ($R$), and (3) current-strength ($C$), being simply proportional to the first two quantities, and proportional to the square of the third. Putting together the three elements into one expression (see § 105, § 238), we can write in symbols,

$$H \text{ [calories]} = \frac{R}{4.2} \times C^2 \times T \text{ [ohms — amperes — seconds]}. \tag{34}$$

The words within square brackets are added to emphasize the units in which heat-quantity, electric resistance, current-strength, and time are to be measured, in order that this numerical relation may remain true. It is instructive to review the long series of related ideas that enter into the above equation, starting with the first crude perception of phenomena, and attaining clearness through the recognition and selection of measurable quantities. Remember, too, that anything said in these pages can be only the barest suggestion of the labor and the genius which the task has demanded.

**245.** The changes back and forth between mechanical work and electrical energy are presented daily in so many examples, that we shall take one step further here, with the aid of the data now before us, and point out how such transformations of energy can be put upon a numerical basis for calculation. The link connecting work and electrical energy is, of course, the mechanical equivalent of heat (see § 146). The fact that 42,800 gr.-cm. of work are represented in 1 calorie of heat is expressed in the equation,

$$\frac{\text{Work[gram-centimeters]}}{42{,}800} = \text{Heat-quantity[calories]}. \quad (35)$$

Before comparing Equations (35) and (34), it is desirable to restate the second member of the latter in a form better adapted to our present use of it. If $E$ is the voltage active between the ends of the resistance $R$ ohms, the product $C^2R$ can be written $EC$ (see § 242); so that equating the equivalent of heat-quantity in terms of electrical energy to its equivalent in terms of work gives

$$\frac{R}{4.2} \times C^2 \times T = \frac{ECT}{4.2}\,\text{[volts — amperes — seconds]}$$
$$= \frac{\text{Work [gram-centimeters]}}{42{,}800}. \quad (36)$$

The words in square brackets call attention to the units, as before.

Uniting the numerical factors $\frac{1}{42{,}800}$ and $\frac{1}{4.2}$ into one, we find

$$10{,}200\ ECT\,\text{[volts — amperes — seconds]}$$
$$= \text{Work[gram-centimeters]}. \quad (37)$$

But an electromotive force $E$ may be active in overcoming a reversed electromotive force, instead of a passive resistance (see § 239), and Equation (37) is equally applicable to either arrangement. The *equivalent* of work is obtained as heat in a resistance; but work itself is furnished directly by means of a motor, or the possibilities of work by means of a storage battery. Here, as elsewhere, power, or rate of working, is practically more important than work (see § 171); and in Equation (37) we can read that 10,200 gr.-cm. of work a second, or its equivalent, are represented in the form of electrical energy, wherever one volt of electromotive force is active, and maintains one ampere of current.

One horse-power is the name for a working rate of $(75 \times 10^5)$ gr.-cm. a second (see § 171). What values of voltage and current-strength correspond to one horse-power?

The voltage between the terminals of a glow lamp is 110 volts, and the current sent through it is one ampere. How many horse-power are represented by the electrical energy expended upon 50 such lamps?

The motor of a trolley car is operated with a voltage of 500 volts, and a current-strength of 15 amperes. How many horse-power are supplied to the motor? If its electric resistance is 0.8 ohm, how much power is wasted as heat?

Reference 50 indicates several directions in which the energy of electric currents has been exploited during the past fifty years.

# CHAPTER XVIII

## ELECTRIFICATION

**246.** Many hundreds of years before the existence of electric currents was suspected, some electrical phenomena were known, as subjects for wonder at least. These were observed when amber was rubbed, and they consisted in its attraction for small pieces of straw or similar light objects, shown by its power to lift them. This behavior of amber is one example of what is now called **electrification**; amber and a number of other substances can be electrified by rubbing them, and one outward sign of their condition is the attraction that they exert (Ex. 174). The original connection of amber with such effects is recorded in the word "electricity."[1] The most instructive aspects of electrification are those which have led to its inclusion with the phenomena of electric currents that we have been studying. Some of them we shall speak of in an elementary way; and, in passing, it will be profitable to notice certain points of likeness and difference in the action of electrified bodies and of steel magnets.

After the attractions between electrified bodies and small unelectrified objects, the next feature to be distinguished is the mutual repulsion of some electrified bodies, and the mutual attraction of others (Ex. 175). This difference in their action makes it natural to recognize

[1] Consult the dictionary for its etymology.

two kinds of electrification, as we identify two kinds of magnetic polarity. The type of one variety is the state assumed by *glass* when rubbed with silk, and it is named **vitreous electrification** for that reason; the second is called **resinous electrification**, with a reference to an early method of producing it, although it is perhaps shown most strongly by hard rubber when excited with cat's fur. The two kinds of electrification appear simultaneously, one on each of the different surfaces that are in contact, unless the conditions are such that one or both can "escape." The tendency of electrified bodies to lose their peculiar condition is very marked. It will be noticed at once that the substances which are experimentally favorable for showing the phenomena are all good insulators; that is, very bad conductors (see § 234). And even they become electrically neutral in a short time, if their surfaces are damp or dusty. The suggestion is strong, that retaining electrification depends upon preventing electric conduction completely. The contact of different substances can be proved to give rise to electrification in many instances where attraction or repulsion is not found ordinarily, if especial pains are taken to guard against conduction.

Compare magnetic and electric forces: —

(1) As regards their relative magnitude, and the rule applying to attraction and repulsion.

(2) As regards variety in the materials between which the attractions can be exhibited.

Do you find bodies permanently electrified, which would correspond to hardened steel magnets?

**247**. If an electrified body touches other (insulated) bodies, its particular state can be imparted to them, the evidence being the repulsion that succeeds the first attrac-

tion, if the circumstances permit the motions to be visible (Ex. 176).

In what two respects does the result here differ from that shown when soft iron, or hard steel, is brought into contact with the pole of a magnet? Is there any indication that the electrified condition is *shared* between two bodies (see § 221, second paragraph)? Does the relative size of the bodies brought into contact influence the effect (Ex.)?

The slow "escape" of electrification can be regarded as imparting an electrified condition to a much larger body, generally the earth.

A partial relief from electrification may take place suddenly, with the accompaniment of a spark (Ex. 177); this is often seen and heard on rubbing a live cat's fur with a dry hand, in front of a fire, where the humidity is small. Under like favorable conditions of humidity, too, gas can be lighted with a spark between finger and burner, after shuffling across a carpet in soft slippers.

## ELECTRIC INDUCTION

**248.** Electrification can be produced in a second body under the influence of one already electrified, the two being in each other's neighborhood, but not connected by any conductor (Ex. 178). This effect is termed electrifying by **induction**; it is stronger, other things equal, the closer the surfaces are together, so they are often contrived to be parallel and separated by a thin layer of a good insulator like glass; the **Leyden jar** is planned in that way. The electric polarity developed by induction shows the same arrangement as magnetic polarity under

similar circumstances (see § 224, end); opposite electrifications appear as closer neighbors, and the remoter parts of the two bodies are in the same condition.

The experiments have proved that the results of electrifying by induction may disappear on removing the body that caused them; or the difference of condition may remain, if the induced electrifications of different kind can be separated while the inducing influence is still active. A method often followed in securing the latter effect is to connect a smaller conducting body with the earth by a wire during the first stage of setting up the induction, thus including the earth in the distribution of electrification. On removing the wire while the inducing influence is still being exerted, the polarity of the smaller body is retained after the induction ceases. Consider the manipulation of the **electrophorus** from this point of view (Ex.).

Notice the prominent part that conducting materials play in allowing all these effects of induction to develop freely. A body as a whole may need to be insulated in order to retain its electrification, but its surface of conducting substance seems essential in permitting electric polarity to be established and removed quickly. The conditions under which electric currents can circulate are those which favor the ready production and removal of electrification by induction (see § 246).

When a body is left electrified after induction has ceased, is this a consequence of *sharing* electrification with the body originally electrified? Energy has somehow been communicated to a body electrified by induction; it can do work in attracting other things to it, and a certain quantity of heat is represented in the sparks obtainable

from it. Where in the process of electrification was the equivalent for this energy supplied?

Compare magnetization and electrification as results of a process called "induction" in both cases. Can magnetic polarities be separated like the electric polarities?

## CONNECTION WITH ELECTRIC CURRENTS

**249.** The suggestions made in the preceding sections, that electric currents are circulating during the production and disappearance of electrification, is borne out fully by experimental evidence (Ex. 179). The currents are transient, but, where they last long enough to be tested, they exhibit every property by which we are enabled to recognize any electric currents: (1) the conductors carrying them are temporary magnets; (2) they are capable of producing chemical decomposition; (3) they heat the metals and the air through which they pass (Ref. 51).

The phenomena in the secondary circuit of an induction coil are a stepping-stone in the gap between the electric currents of batteries or dynamos, and those excited during *changes* in electrification. The induction coil can be used to "charge" a Leyden jar; it gives sparks through air like such a jar, the same physiological effect of "shock" being felt in both cases; and electric attractions or repulsions are shown by the induction coil (Ex. 180). The large electromotive force and the small (average) current-strength of the secondary coil as usually constructed have been mentioned already (see § 241). So also the electromotive forces concerned in electrification are large, as shown by their power to utilize channels of great resistance, and the magnetic properties of the corresponding currents escape notice unless looked for carefully.

# REFERENCES TO COLLATERAL READING

THE titles of the works referred to here and in the Outline of Experiments that follows are contained in the list below. Those which have been quoted often are used in shorter form, and this is indicated within square brackets after the full title in such cases. A word of comment about the general scope or character of a book has been added sometimes, where it seemed likely to prove helpful.

It should be remembered that this list is not in its intention even an elementary bibliography. Neither is it claimed that the selection cannot be improved by additions and substitutions, if anybody will make serious effort in that direction. But the books recommended have been proved useful for the ends here in view; while the fact that they can be easily acquired for school libraries, and made really accessible to pupils, is not without weight. The attempt has been made, as a rule, to render the references pointed by quoting page or heading, in the belief that much is gained for young minds by directing attention to some definite idea or particular statement. At the same time, this must not be construed too narrowly; the page named is often only a starting-point, and it will be found profitable to follow its clews backward and forward in the context. In this respect, especially, a given reference may appeal very differently to a teacher and to his pupils. The *Encyclopædia Britannica* has been drawn upon freely, because it is likely to be included in a school library. Some of its scientific articles — not merely those on biography — are admirably suited to the use of them suggested here. But others I have cited with misgivings, lest inexperience get lost amid the extent of them. Yet good material can be "tried out" of such articles, and of many others that a little pains will discover, if the thought of teachers is turned to those matters. I hope that the thought of intelligent teachers will be diverted toward strengthening these aids to successful instruction.

## LIST OF TITLES

BOYS, *Soap-bubbles* (Society for promoting Christian Knowledge). Lectures prepared for children, and full of ingenious experiment simply contrived.

CAJORI, *History of Physics* (Macmillan). Professor Cajori has done us a real service in publishing this history. It is well conceived, and executed in good proportion as regards emphasis and selection of material. [*Cajori.*]

CARHART, *Primary Batteries* (Allyn & Bacon).

CHUTE, *Practical Physics* (Heath). See comment under Outline of Experiments. [*Chute.*]

CLERKE, *History of Astronomy* (Macmillan).

DANIELL, *Principles of Physics* (Macmillan). It contains some distinctively good accounts of phenomena, but is disfigured with kinematics, etc., out of proportion to its general scope.

EBERT, *Magnetic Fields of Force* (Longmans). An elementary presentation of phenomena in the magnetic field as determined by action in the "medium." Teachers ought to find it full of suggestions.

*Encyclopædia Britannica.* Reference is aided, where necessary, by giving subheading, as well as main topic. On the few occasions where pages are quoted, the numbering is that of the Ninth *English* edition. [*Enc.*]

EVERETT-DESCHANEL, *Natural Philosophy* (Appletons). Professor Everett's additions are perhaps the most valuable part of this translation. The book is "old-fashioned," but substantial in the subjects where the fashions have not changed. The paging varies in the editions on sale; so I have tried to indicate chapters. [*Deschanel.*]

EVERETT, *Units and Physical Constants* (Macmillan).

*Johnson's Cyclopædia* (Johnson Company).

LE CONTE, *Sight* (Appletons: International Science Series). Written lucidly, with the sure touch of ripe scholarship. The author had few equals in popular exposition.

LOCKYER, *Spectrum Analysis* (Appletons: International Science Series).

LODGE, *Modern Views of Electricity* (Macmillan). Helpful to the teacher in forming the reserves of knowledge with which he strengthens his teaching, though he makes no effort to impart them directly to young pupils.

MACH, *Science of Mechanics* (Open Court Publishing Company). A book unique in its excellence on the ground that it covers — the historical development of ideas and principles in mechanics. [*Mach.*]

MADAN, *Elementary Treatise on Heat* (Rivingtons). Rich in material wisely chosen for the stage of secondary education. A book that deserves to be widely known. [*Madan.*]

ROOD, *Modern Chromatics* (Appletons: International Science Series).

ROUTLEDGE, *Popular History of Science* (Routledge & Sons). A serviceable compilation, including more of the text-book matter than Cajori, and more popular in tone. [*Routledge.*]

STEWART, *Conservation of Energy* (Appletons: International Science Series). The subject deserves dwelling upon, and should not be disposed of in a paragraph. This book puts the case well, and the Appendix by Le Conte is valuable.

STEWART, *Elementary Treatise on Heat* (Macmillan). Strong in such material as numerical data, accounts of heat phenomena in general, and particularly of heat as connected with radiation. [*Stewart.*]

STONE, *Experimental Physics* (Ginn). A book written with a clear purpose, and presenting many good points as a guide for laboratory work. I should like to see its boundaries widened at some places. [*Stone.*]

TAIT, *Heat* (Macmillan). All three books of Professor Tait that are mentioned here should be used without their mathematical parts for our immediate ends.

TAIT, *Light* (Macmillan).

TAIT, *Properties of Matter* (Macmillan). A valuable collection of many suggestive phenomena and discussions not to be paralleled elsewhere. [*Properties of Matter.*]

TARR, *Elementary Physical Geography* (Macmillan). [*Tarr.*]

THOMPSON, S. P., *Faraday: his Life and Work* (Macmillan).

TYNDALL, *Heat a Mode of Motion* (Appletons). [*Tyndall, Heat.*]

TYNDALL, *Sound* (Appletons).

WATSON, *Text-book of Physics* (Longmans). A useful compendium, representing college physics in cyclopædia fashion. To be referred to generally for enlargement of subjects comprised in this text-book. [*Watson.*]

ZAHM, *Sound and Music* (McClurg).

## LIST OF REFERENCES

The number of each Reference, which is attached to it in the body of the text, is printed first and in full-faced type. The number of the section where it occurs is added for convenience.

**1**, § 10. *Cajori*, p. 280. *Enc.*, ACADEMY: Scientific Academies, Italy. *Routledge*, p. 178. *Properties of Matter*, p. 87.

**2**, § 14. *Cajori*, p. 66. *Enc.*, GUERICKE. *Routledge*, p. 172.

**3**, § 20. *Cajori*, p. 31, p. 64. *Enc.*, GALILEO. *Mach*, p. 113. *Routledge*, p. 104.

**4**, § 22. *Johnson's Cyclopædia*, METRIC SYSTEM. *Enc.*, EARTH (Figure of); and WEIGHTS AND MEASURES: Commercial. EVERETT, *Units and Physical Constants*, passim.

A good single reference on the general history and bearings of the Metric System seems hard to find. *Johnson's Cyclopædia* gives a fair summary. The *Britannica* articles are cumbrous; what is necessary for the present purpose must be selected at some trouble and put together. I should introduce the full Reference gradually, as the quantities connected with the Metric System present themselves.

**5**, § 29. *Cajori*, p. 3, p. 25. *Routledge*, p. 39. *Properties of Matter*, p. 86; notice the point about condensation raised here.

**6**, § 48. *Cajori*, p. 45, p. 64. *Enc.*, TORRICELLI. *Routledge*, p. 168.

**7**, § 49. *Cajori*, p. 62. *Routledge*, p. 169.

**8**, § 51. *Cajori*, p. 65. *Routledge*, p. 170.

**9**, § 61. *Enc.*, ARTESIAN WELLS. *Tarr*, p. 229.

**10**, § 63. *Cajori*, p. 281. *Properties of Matter*, p. 186. *Watson*, p. 181.

**11**, § 63. *Cajori*, p. 70. *Enc.*, BOYLE (Robert). *Properties of Matter*, p. 161, p. 169.

**12**, § 63. *Cajori*, pp. 199–204. *Properties of Matter*, p. 171. *Watson*, p. 151.

**13**, § 82. BOYS, *Soap-bubbles*. *Enc.*, PLATEAU. Also CAPILLARY ACTION: Phenomena arising from the variation of surface-tension. *Properties of Matter*, Chapter 12, Cohesion and Capillarity (the descriptive parts); notice the Atmometer, p. 258.

**14**, § 91. *Cajori*, p. 89. *Enc.*, THERMOMETER. *Madan*, p. 90 and ff. TAIT, *Heat*, Chapter 7, Thermometers.

**15**, § 99. *Cajori*, p. 194. *Madan*, p. 69. *Stewart*, p. 46. TAIT, *Heat*, p. 89.

**16**, § 100. *Madan*, p. 272. *Tarr*, pp. 179–191. Note the caution on p. 185.

**17**, § 107. *Cajori*, p. 196. *Stewart*, p. 64. TAIT, *Heat*, p. 100. *Watson*, p. 225.

**18**, § 110. *Deschanel*, p. 493 (Terrestrial Temperature and Winds). *Madan*, p. 283. *Tarr*, Chapters 4 and 5. TYNDALL, *Heat*, p. 206.

**19**, § 122. *Stewart*, p. 92, p. 99. TAIT, *Heat*, p. 120. TYNDALL, *Heat*, p. 148, p. 221.

**20**, § 126. *Cajori*, p. 115. *Enc.*, BLACK (Joseph). *Stewart*, p. 307.

**21**, § 127. *Madan*, p. 140. *Tarr*, p. 45.

**22**, § 137. *Deschanel*, p. 332.

**23**, § 142. *Cajori*, p. 190. *Deschanel*, p. 445 (Thermodynamics: the historical and descriptive parts of two chapters). *Enc.*, DAVY. Also THOMPSON (Sir Benjamin). *Madan*, p. 349 (Chapter 9). TYNDALL, *Heat*, p. 39.

**24**, § 146. *Cajori*, p. 210. *Enc.*, ENERGY. *Stewart*, p. 330.

**25**, § 150. TYNDALL, *Heat*, p. 123, p. 537.

**26**, § 155. *Stewart*, pp. 174–254. TYNDALL, *Heat*, pp. 269–358. Select material, however, in both cases, among much that is of less value for the present purpose.

**27**, § 156. *Cajori*, p. 112. *Deschanel*, p. 467 (Steam and other Heat-engines). *Enc.*, STEAM-ENGINE: Early history of the steam-engine. Also WATT (James). *Madan*, p. 367.

**28**, § 167. *Mach*, p. 128. *Routledge*, p. 162. And see Reference 3.

**29**, § 169. STEWART, *Conservation of Energy:* The book as a presentation of the subject. Add *Cajori*, p. 209. *Madan*, p. 418.

**30**, § 173. *Cajori*, p. 53. *Mach*, p. 251.

**31**, § 174. *Cajori*, p. 56. *Enc.*, NEWTON (selecting the personal parts). *Mach*, p. 190. *Routledge*, p. 180.

**32**, § 181. TYNDALL, *Sound*, p. 214 (Chapter 6).

**33**, § 186. *Enc.*, MUSIC: Scientific basis. TYNDALL, *Sound*, p. 257 (Chapter 7). ZAHM, *Sound and Music;* especially Chapter 10, but the historical and descriptive parts of other chapters can be made useful.

**34**, § 206. *Cajori*, p. 77. *Enc.*, LIGHT: Velocity of light. Also ROEMER. Also PARALLAX: p. 245 (solar parallax), p. 251 (the physical method). *Routledge*, p. 228.

**35**, § 206. *Cajori*, p. 151. *Deschanel*, p. 955 (p. 90 of the separate volume *Sound and Light*). *Routledge*, p. 505. TAIT, *Light*, p. 52.

**36**, § 207. *Cajori*, p. 149. *Enc.*, FOUCAULT. References 34, 35, 36 overlap necessarily. Use them together.

**37**, § 207. *Cajori*, p. 76. *Routledge*, p. 155.

**38**, § 214. *Cajori*, p. 82. *Routledge*, p. 217. TAIT, *Light*, p. 84.

**39**, § 216. *Enc.*, EYE. LE CONTE, *Sight*.

**40**, § 217. *Cajori*, p. 37. *Deschanel*, the chapter: Vision and optical instruments, in its easier descriptive parts. *Enc.*, MICROSCOPE. Also TELESCOPE. The easier historical and descriptive parts selected from both articles. *Routledge*, p. 108.

**41**, § 219. *Cajori*, pp. 157–171. CLERKE, *History of Astronomy*, Part II, Chapter 1. *Enc.*, SPECTROSCOPY. Also FRAUNHOFER. LOCKYER, *Spectrum Analysis*, passim. *Routledge*, p. 476.

**42**, § 220. DANIELL, *Principles of Physics*, p. 497.

**43**, § 222. *Cajori*, pp. 41–47. *Enc.*, COMPASS. Also MAGNETISM: Leading phenomena; and Forms, construction, and preservation of magnets. Further, METEOROLOGY: Hypothetical views regarding the connection between the state of the sun and terrestrial magnetism. CLERKE (Ref. 41) also speaks of sun spots and magnetism.

**44**, § 228. *Cajori*, pp. 223–227. *Enc.*, AMPÈRE (A. M.). Also ELECTRICITY: History (this article includes also Davy, Faraday, Galvani, Volta. Ref. 47 and 48). *Routledge*, p. 560, p. 563.

**45**, § 229. *Cajori*, p. 273. *Enc.*, MORSE. Also TELEGRAPH. *Routledge*, p. 567.

**46**, § 231. CARHART, *Primary Batteries.*

**47**, § 232. *Cajori*, pp. 234–246. *Enc.*, FARADAY. *Routledge*, p. 575. S. P. THOMPSON, *Faraday: his Life and Work.*

**48**, § 236. *Cajori*, pp. 132–135, p. 215, p. 238. *Enc.*, GALVANI. Also VOLTA. See further under Ref. 44. *Routledge*, p. 548.

**49**, § 239. *Cajori*, pp. 227–232.

**50**, § 245. Telephone: *Cajori*, p. 276. *Enc.*, TELEPHONE. We must not look to the older standard books for an account of the most modern forms of electrical contrivances. If satisfactory descriptions are needed of the items mentioned here, they will scarcely be found in the books of a school library; they must be gleaned with caution from magazines, journals, and recent technical books. Besides the Telegraph and Telephone, we name Electric Lighting and Power; Electroplating and Electrometallurgy; Transformers; Electric Welding and the Electric Furnace.

**51**, § 249. Franklin's work should be noted. See *Cajori*, pp. 120–127. *Routledge*, p. 326. Teachers will find much that is suggestive in LODGE, *Modern Views of Electricity;* but it is rather "strong meat" for pupils. Faraday was testing the identity of "frictional" and "current" electricity when his work led him to discover the laws of electrolysis.

# OUTLINE OF EXPERIMENTS

ACCORDING to the plan announced in the PREFACE (p. xi), the accompanying list of experiments is not intended to serve as a laboratory guide, but only to indicate the character of the experimental work that is fitted to prepare the way for particular conclusions in the text, and enforce them. In carrying out this idea, it became advisable to utilize printed descriptions of suitable exercises, partly because the fact that they are thus published is presumptive evidence that briefer allusion to them will be readily understood. And it is evidently most convenient for everybody concerned to refer to one book so far as possible. Therefore the references made are most largely to CHUTE, *Practical Physics*, as being the collection, among those which have come to my notice, that includes the greatest proportion of what is required to afford experimental foundation for the text. This is said without implying that I should use the laboratory manual in question with classes, or consider the form of experiment there given always the best. But the author did good service for the teaching of Physics, in my opinion,— and did it early in the development of laboratory instruction for schools,— by the publication of a book so excellently planned, and offering such a wide and varied choice of possible experiments. The Preface and remarks "To the Teacher" are wisely conceived, and contain some

truths which are apparently still undiscovered by many teachers of science. Most of us, indeed, might feel repaid for the time spent in reading those pages with attention.

Inasmuch as the present selection of experiments is meant primarily for the use of teachers; that is, for persons who are already experts in the subject, I have not hesitated to speak with a certain brevity as regards details in describing apparatus and its arrangement. It may be noticed, too, that the words of commentary or suggestion added here and there are directed to teachers rather than to pupils; and sometimes these remarks supplement a part of the text that is purposely left somewhat bare or incomplete.

The experiments include some that are certainly better suited to be laboratory exercises for the pupils; some just as clearly adapted to be class experiments; and a third group that may be treated either way according to circumstances. Those circumstances involve the actual condition of an individual class — among other things. It is not well to be rigid about such matters, so I have not marked experiments as belonging to one or another of the three groups. But we must agree about one idea, — the equipment of the school must be adequate to *teach Physics experimentally*. There will be no life where phenomena are made a perfunctory sequel to the study of a book.

The number prefixed to each experiment is that which is attached to it in the body of the present text, and in order to facilitate reference this is followed by the number of the section in which the particular experiment is first mentioned. Quotations from [*Chute*] and [*Stone*] are by page numbers, accompanied (within parentheses) by the number of the experiments in those manuals.

## EXPERIMENTS

**1**, § 10. A bulb with narrow stem, filled with water that has been boiled to expel air, and heated in a gas-flame or a vessel of hot water. This is the qualitative introduction to Experiment 64, § 97. The presentation of the same phenomena, first from the qualitative side, and then quantitatively, is intentional in this case and a number of others. Chute, p. 142 (238).

**2**, § 10. A test-tube, partly filled with water (or mercury) and inverted in a vessel of water (or mercury), shows all that is necessary here; as the test-tube is raised and lowered, the volume occupied by the air changes.

**3**, § 11. The general form of such experiments is sufficiently indicated in the text. In speaking of these matters at once, and thus qualifying our statements about liquids at the outset, the intention is to avoid the necessity of retraction later, when we come to describe capillary phenomena (§ 80).

**4**, § 13. It seems desirable to illustrate the arrangement of a diving bell and of a caisson for excavation under water. A bottle from which the bottom has been removed is sunk, neck upward, in a vessel of water. Displace the water by pumping in air with a bicycle pump attached to the neck of the bottle, using a tap or valve if necessary.

**5**, § 15. Both these experiments are well known. The former is more suitable for beginners, since some danger attends the mixing of strong sulphuric acid with water, especially if the *water is poured into the acid.* Chute, p. 41 (54); Watson, p. 140.

**6**, § 16. Again qualitative, and preceding the measurement of Experiment 70, § 102. Chute, p. 140 (233), etc.

The contraction on cooling below room-temperature should be exhibited and insisted upon. There is a tendency to speak exclusively of *heating* and *expansion*. With beginners, the reverse process should be made equally prominent.

**7**, § 19. The experiments instanced in the text are samples only. They may be varied and multiplied with small expenditure of time. The early connection of weight with other forms of force is important, in order to implant the right point of view (see § 25).

**8**, § 20. To extinguish a lighted candle by pouring carbon dioxide over it from a jar is still an instructive experiment. It will be remembered that Tyndall made a stream of this gas turn light paddle-wheels, as it flowed down an inclined trough.

**9**, § 20. The essential idea here is the conception of differential effect. Acetylene is now so common that soap-bubbles might be blown with it, giving results intermediate between coal-gas and carbon dioxide (sp. wts. referred to air, 0.5 and 1.5).

**10**, § 20. The bulbs of electric glow lamps (preferably the large size, 32 c.p.) form a good starting-point for this experiment, because the exhaustion has been carried far beyond that obtainable with an ordinary air-pump. The exhausted bulb is first counterpoised, then air is admitted, and the disturbance of balance noted; this is apparent on a "trip-scale."[1]

**11**, § 23. This is the standard experiment. Chute, p. 119 (185). A light ball of glass (Christmas-tree

[1] The above method may be made quantitative, and even the specific weights of some gases roughly determined, as Mr. A. W. Gray shows in "School Science." I am unable to give reference, as this is written before the note is published [February, 1902].

ornament) can be used, counterpoising it with brass on a splinter of wood, if the ball is strong enough to withstand the pressure from inside, on exhausting the air around it.

**12**, § 24. The Jolly spring-balance (Chute, p. 25) is well adapted to calibration by the sensitiveness of its spring. The way is thus prepared by the pupil's own efforts, for the later use of this balance in measuring specific weights (Experiment 16, § 31).

**13**, § 27. This general method should be illustrated: —

(1) As applied to liquids. Use the "specific gravity (*i.e.* specific *weight*) bottle" preferably in a simple form; not a "glass stopper with capillary opening." Chute, p. 121 (190).

(2) As applied to solids. Use the "overflow beaker," Stone, p. 12 (6), but with an object that sinks.

Note that specific weight is measured here according to the terms of its definition, and without reference to the principle of Archimedes. The idea that this principle necessarily underlies specific weight should not be encouraged (see § 31).

**14**, § 28. The intention here is that illustrations shall be presented to emphasize the part played by the liquid as well as by the solid; that is, to fix the habit of regarding specific weight as a ratio. Also, by the use of examples like a closed bottle loaded with different quantities of shot, to enforce still further the idea of average specific weight (see § 27 (1)), and of equal buoyancy with varying weight.

**15**, § 29. The conditions will bear more study than is commonly given to them. The form adopted in Chute, p. 116 (180), seems good, because it includes an experimental answer to the question, "Has the entire weight of

the immersed body still to be supported; and, if so, how is that done?" Follow the suggestion, too, that the experiment should not be confined to the one liquid — water. Neither should the case of a floating body be neglected. Chute, p. 118 (183). Stone, p. 12 (6).

**16**, § 31. This range of experiments is usually rather overdone (proportionately) than neglected. But the three cases should be taken up: (1) a solid that sinks; (2) a solid that needs a sinker; (3) a solid of known specific weight, used in finding the specific weight of a liquid. If porous substances like wood are used (paraffined or varnished), it should be brought out that the specific weight found is the average for the substance proper and the pores.

**17**, § 31. The idea of testing an instrument that is already graduated can be used here; the reading of the hydrometer being observed in water, and the readings in some other liquids being compared with the pupil's own results for their specific weights.

**18**, § 31. Nicholson's hydrometer is mentioned, partly because good lines of questioning can be founded on its use.

**19**, § 33. Besides the example of layers formed by water and oil, etc., it is instructive to notice the threads of specifically heavier solution falling away from a soluble, colored crystal suspended near the surface of water.

A ballasted eggshell can be adjusted to float, part above and part below the boundary of strong brine and kerosene. Query: "How can that condition be expressed?"

**20**, § 37. It seems desirable to emphasize this thought by direct experiment, providing counterpoised vessels of different forms, and pouring the same portion of liquid into them successively.

**21**, § 38. This experiment is described in detail by Stone, p. 27 (19).

**22**, § 40. Stone, p. 24 (17).

**23**, § 41. Any of the common range of experiments with the air-pump, exhibiting effects of (unbalanced) atmospheric pressure.

**24**, § 42. Stone, p. 26 (18); and compare Chute, p. 103 (155).

**25**, § 48. Chute, p. 104 (158). The vacuum can be much improved, after it is first formed, by closing the lower end of the tube (still beneath the mercury surface), removing it, and allowing the mercury in it to run *slowly* back and forth several times. The air-bubbles adhering to the glass expand into the vacuum, and are removed more effectively than by the use of a wire. This process is sometimes described as "rinsing the tube with the vacuum." Now place the tube with open end up, fill completely, and invert again.

**26**, § 58. The usual glass models of a lifting pump and a forcing pump can be made to do good service here.

**27**, § 60. Chute, p. 113 (172, 173). It seems preferable to avoid the form of statement (sometimes found in print), "The velocity of flow through a siphon is *proportional* to the difference of level," etc.

**28**, § 60. Chute, p. 114 (174).

**29**, § 62. Stone, p. 35 (24). Experiment 31 below may be *substituted* here.

**30**, § 62. Stone, p. 37 (25). Chute, p. 125 (197).

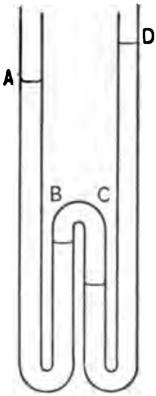

FIG. 102.

**31**, § 62. This form of experiment is added (Fig. 102),

although it is in principle a repetition of Experiment 29: (1) because it has the experimental advantage of being applicable to liquids that would mix, and (2) because good searching questions can be connected with it. The space $BC$ is occupied by air (plus vapor of the liquids), the columns of liquid extend round the lower bends into the arms $A$ and $D$.

**32**, § 63. Boyle's law. The experimental work should be done with some form of apparatus that permits (1) continuous adjustment of pressure, and (2) the use of pressure below that of the atmosphere. The rigid U-tube of glass often employed is inadequate for the proper scope of the experiment. In Fig. 103, $SS$ is a fixed scale, against the edges of which the glass tubes, $A$ and $B$, can be clamped in any position by the screws, $C$ and $C_1$. These tubes are connected by a loop of rubber tube and contain mercury as shown. $B$ is open, $A$ is closed and made *flat* at the upper end, in order that proportional volumes of contained air can be read on the scale.

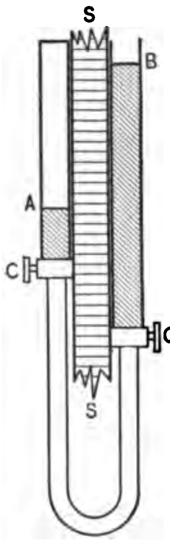

FIG. 103.

**33**, § 63. Applying a hot-water jacket or a gas-flame to the tube $A$ (Fig. 103), show (qualitatively) that both the volume and the pressure of the enclosed air can be increased. Or show the same phenomena in other simple ways. The quantitative side of this matter appears in Experiment 71.

**34**, § 63. Provide a mercury cistern 30 to 40 cm. deep, and large enough to admit a barometer tube freely.

"Half-inch" gas pipe will do, tapped into a two-inch cap," in order to form a broader cup at the upper end, and make manipulation easier. Fill a barometer tube with mercury, taking extra care to remove air bubbles, and invert it in the cistern. Introduce ether into the vacuum drop by drop with a pipette, until liquid ether can be made to appear on lowering the tube 20 or 30 cm. into the cistern. The gradual introduction of ether prevents violent oscillations of the mercury, and hits the mark of adjustment besides (Watson, p. 251).

There is an apparent disposition to displace this simple experiment in favor of less instructive material, especially in making out the lists of the shorter laboratory manuals. A fundamental distinction between gases and vapors is then left without experimental foundation (see further, Experiment 82 below).

**35**, § 65. Chute, p. 118 (184), where the traditional "bottle imp" is very sensibly discarded.

**36**, § 66. Fused potassium hydrate gives a warm solution, though dissolved in cold water. Heating accompanies the taking up of water of crystallization by some anhydrous salts, *e.g.* copper sulphate.

**37**, § 67. Chute, p. 68 (106), substituting coal-gas for hydrogen, where the former is more easily procurable.

**38**, § 68. Chute, p. 66 (102). Coal-gas can be used successfully here, too, instead of hydrogen. Holding the bell-jar as shown in the figure (Chute, Fig. 43), an atmosphere of gas is supplied from a rubber tube, and maintained round the porous cup as long as necessary (see further, Chute, p. 38 (49)).

**39** and **40**, § 70. Chute, p. 61 (87). The general facts that saturation-points differ, and that the salt is

obtainable by evaporation, may be made evident without carrying on strictly quantitative experiments.

**41**, § 71. Water and crystals of copper sulphate furnish a good example, in which the process of diffusion continues for months in a tall cylindrical jar, care being exercised to avoid shaking, and changes of temperature that would result in convection currents.

**42**, § 72. The three types are exemplified by (1) water and kerosene, (2) alcohol and water, and (3) ether and water.

**43**, § 73. Ammonia gas to be absorbed by a fresh portion of water is obtained readily on heating a (larger) quantity of strong aqueous ammonia. As a means of making the volume of gas impressive, pass it through a "wash bottle" containing cold strong solution of ammonia, and watch the stream of bubbles.

**44**, § 73. Tap water, solution of ammonia, seltzer water, all give off bubbles of gas copiously, when the atmospheric pressure on their surface is relieved with an air-pump. Change of saturation by heating has been utilized in Experiment 43 (see also Chute, p. 40 (52)).

**45**, § 74. For example, Chute, p. 41 (53).

**46**, § 74. At several points in the text, the material presented is intended to suggest an apparently stable condition as one of balance between loss and gain that are both actually occurring. See, for example, the thought connected with Fig. 37 (§ 78).

**47**, § 76. Chute, p. 46 (64).

**48**, § 79. A good example is the absorption of ammonia gas by charcoal. The gas is contained in a wide test-tube over mercury, and the charcoal is introduced, having been first strongly heated, in order to dry it and free it from

gases that it might have absorbed previously (Watson, p. 169).

**49**, § 79. Calcium chloride, strong sulphuric acid, lime, potassium hydrate, and phosphorus pentoxide are instances of hygroscopic substances.

**50**, § 79. The allusion here is to the action of platinum sponge in bringing about chemical union of hydrogen and oxygen. Döbereiner utilized this in the so-called "philosopher's lamp."

**51**, § 79. Hang a spiral of platinum wire (about ten turns) in the flame of a strong Bunsen burner, and let it become bright red-hot. Turn off the gas until the wire falls a little below the kindling temperature, and then turn it on again. If the wire has been caught within the right range of temperature, it will grow hotter in the unignited mixture of gas and air, and finally set light to it.

**52**, § 80. Tubes of equal bore in vessels of mercury and of water, showing depression and elevation of the liquids.

**53**, § 80. To emphasize this aspect of the thought, compare the behavior of mercury (and water) in two U-tubes, having one arm of the same bore; but the second arm is of smaller bore in one case, and of larger bore in the other.

**54**, § 80. This may be omitted if Experiment 3 (§ 11) has been pushed far enough to cover the point.

**55**, § 82. (1) See Fig. 104, in which *B* is a bulb of glass, ballasted with mercury or shot until it floats in water, somewhat in the position shown. A piece of fine wire-gauze *W* is attached to the stem with wax, so that the capillary action between its meshes and the

water holds *W* in the level *AC* on pushing the bulb down.

(2) Chute, p. 57 (81). It is perhaps an improvement to make frame and slider of glass, by drawing down glass tubing to the diameter of about number 20 wire. The Jolly balance (Chute, p. 25) is serviceable in measuring the force.

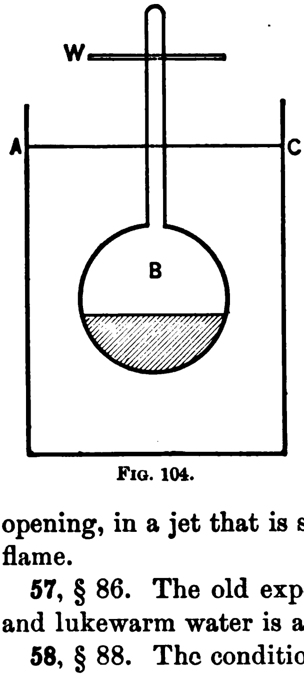

Fig. 104.

(3) Chute, p. 56 (80); the exercise with a loop of thread within the film held by a ring of wire.

(4) The change of shape in an ordinary water-color brush on wetting it.

**56**, § 82. The excess of pressure within a soap-bubble will expel the air through a fine opening, in a jet that is strong enough to affect a candle-flame.

**57**, § 86. The old experiment with vessels of hot, cold, and lukewarm water is a sufficiently good illustration.

**58**, § 88. The condition that the vessel shall be "open" is, of course, merely to simplify matters in their first statement. It is well, perhaps, to magnify the dimensions here, as compared with a thermometer. Blow a (thick-walled) bulb at the end of a small tube, and fill with mercury.

**59**, § 89. This may be omitted, so far as the water is concerned, if Experiment 1 (§ 10) has been worked out well.

**60**, § 89. The common device is to plunge the bulb suddenly into hot water, and notice the first *drop* of the mercury thread. If the bulb be suddenly cooled in very cold brine, a transient *rise* of the thread can be observed.

**61**, § 92. The ordinary procedure in locating the "fixed points." Chute, p. 146 (246).

**62**, § 92. The intention here is only to call attention to the steam pressure as one necessary element, without diverting thought too strongly from what is just now the main idea. Therefore a short and simple experiment will suffice, confined to the effects of pressure greater than that of the atmosphere; for example, Stone, p. 77 (37). The fuller and quantitative consideration is then reserved for Experiment 87 (§ 131).

**63**, § 96. Show that a thermometer hanging in air does not necessarily give the temperature of the air. Radiation from the sun, or an open fire, or a hot stove, or a freezing-mixture, affects the result. Attention may be called to the precautions in this direction at the meteorological stations.

**64**, § 97. Taking equal bulbs with narrow stems (Stone, p. 69 (31)), or equal flasks fitted with corks and tubes, and heating them in the same water-bath, compare the apparent expansions of water and alcohol. Assuming the same expansion for the glass in both cases, the comparison extends to absolute expansion. The next experiment (65) is intended to apply the method of Dulong and Petit (Watson, p. 221). If that be found too difficult, the present experiment should be made quantitative for at least one of the liquids, determining its coefficient of apparent expansion. The general arrangement of Chute, p. 142

(238), replacing sand-bath by water-bath, seems preferable to (239). The projecting tubes can be calibrated easily, and that exercise is profitable.

**65**, § 98. The apparatus of Watson, p. 222 (Fig. 152) can be greatly simplified. The W-tube of Experiment 31 (§ 62) can be adapted to this purpose by fitting "jackets" of glass or metal, for hot and cold water, over the tubes *A* and *D* (Fig. 102).

**66**, § 99. This is the companion to Experiment 63 (§ 96), and is intended to give confidence as regards using thermometers in water-baths, etc. It might therefore better precede Experiments 64 and 65 in actual work.

**67**, § 99. Chute, p. 136 (225). Or a soluble, colored salt like potassium bichromate can be used, contrasting the rapid attainment of homogeneousness with the results of Experiment 41 (§ 71).

**68**, § 100. The maximum contraction of water is best shown in a bulb with narrow stem. The freezing-mixture used should not be too efficient, else it becomes difficult to control and trace the cooling process, and the freezing water bursts the bulb without much notice.

**69**, § 101. This may be omitted if adequate emphasis has been laid upon Experiment 6 (§ 16).

**70**, § 102. Chute, p. 140 (234). Another form of apparatus is described by Stone, p. 85 (40). Our habit is to speak of coefficients of *expansion;* but the instruction should leave the impression plain that they are coefficients of *contraction* also. See Experiments 6 and 64.

**71**, § 106. Chute, p. 143 (241); and the alternative plan of Stone, p. 90 (41).

**72**, § 110. Chute, p. 138 (229).

**73**, § 114. It is desirable to precede measurements of specific heat by qualitative study of the resulting temperatures on mixing: —

(1) Equal weights of hot and cold water.

(2) Unequal weights of water.

(3) Equal weights (or volumes) of hot mercury and cold water.

**74**, § 118. Chute, p. 162 (272). The method of mixture with water can be applied to kerosene; stirring brings the two liquids into intimate contact.

**75**, § 119. Chute, p. 164 (275).

**76**, § 122. The well-known experiment of making a loaded wire (string?) cut through a block of ice, and leave a closed seam behind it. Reference 19; especially Tyndall, Heat, p. 148.

**77**, § 123. Chute, p. 167 (277). Striking results are obtainable by dissolving ammonium nitrate alone.

**78**, § 124. Boil a small quantity of water in a clean test-tube in order to expel dissolved gases, and let it cool to the temperature of the air. If jar or shock and the intrusion of foreign particles are avoided, it will be found possible to retain the water in the liquid form while the cooling is carried gradually to about $-5°$ in a freezing-mixture. Success may be preceded by several failures.

**79**, § 124. Sodium hyposulphite may be "melted in its water of crystallization" in a test-tube, and retain the liquid state upon cooling, if protected against jar and foreign material. A thin layer of olive oil poured gently upon the liquid, before the critical stage of the cooling arrives, is a good protection in this experiment and the one preceding. Sodium sulphate is another salt often employed in exhibiting supersaturation. Chute, p. 168 (282). In

experiments on overcooling and supersaturation, attention should be given to the thermal phenomena that appear when the "abnormal" state is disturbed by shaking, or by introducing a small crystal of the substance that is present in liquid form.

**80**, § 125. Attach a strip of "gold-leaf" to the stopper of a bottle containing a layer of mercury, so that the strip hangs clear of the mercury by 2 or 3 cm. when the stopper is in place. After a few weeks decided signs of amalgamation will show, even at temperatures below 20°.

**81**, § 126. Chute, p. 165 (276).

**82**, § 128. Having produced a good Torricellian vacuum, introduce alcohol or ether with a pipette until some remains in the liquid state, and measure the *depression* of the mercury column corresponding to a given temperature of the air, or of a water-jacket surrounding the tube. It is well to incline the tube until the mercury touches the top, before the ether or alcohol passes in, else the mercury column may be thrown into violent oscillations, and even shatter the tube. The depression caused by water at ordinary room-temperatures can be measured also, as preparation for § 133.

**83**, § 129. Taking a tube in the condition of 1, Fig. 26 (§ 59), introduce ether or alcohol as in Experiment 82, regulating matters so that the final pressure (when some liquid remains unevaporated) is less than atmospheric pressure. Compare the total pressure (air plus ether-vapor) with the sum of the original air pressure and the maximum vapor-pressure of the liquid for the working temperature.

**84**, § 130. The superheating of pure water, to the extent of two or three degrees, is often shown without

special effort, in a clean glass vessel, if the water has been freed from dissolved gases by protracted boiling. Heating in an oil-bath favors this result. In small tubes open at one end, the superheating can be carried much farther by taking precautions in the direction of purity and freedom from jar; but the experiment becomes dangerous.

**85**, § 131. To show the equality of external pressure and vapor-pressure at the boiling-point, fill the closed arm *CB* (Fig. 105), of the U-tube *CBE*, with mercury, and introduce a few drops of water, so that they occupy the top of the arm near *C*. Heat the water in the vessel *AD* to boiling, the arm *E* being open. The mercury level in the two arms becomes the same. Afterward, the same contrivance can be used to *find* the boiling-points of liquids like ether, alcohol, substituting them in turn for the water in the arm *C*; the boiling-point is the temperature of the bath corresponding to equality of level in both arms. And making of *AD* an oil-bath, boiling-points above 100° can be found. For these purposes *CB* may be conveniently about 10 cm. long. But such a bent tube can be adapted to measure maximum vapor-pressures of liquids, above and below their boiling-points, by giving the necessary length to the arm *CB* (see Ex. 82, § 128).

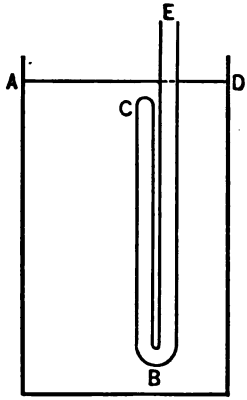

FIG. 105.

**86**, § 131. Chute, p. 151 (255). Then raise the bulb of the thermometer into the steam.

**87**, § 131. To make the experiment quantitative, the steam-point on the scale of the thermometer used should be known accurately, for the barometer height 76 cm. A possible difference from 100° is then allowed for. The tube of Fig. 105 can be used, the barometer height being known, and the temperature of the bath being noted at which the mercury level in *C* is a given number of centimeters above or below the level in *E*. Or a scheme like Stone, Fig. 30 (p. 78), can be adopted for excess of pressure. And pressures below atmospheric pressure may be maintained within a flask with an aspirator or a jet-pump; the ordinary air-pump can scarcely be used for such purposes.

**88**, § 135. A covering of loose cotton-wick on the bulb of a thermometer, the lower ends dipping into water 2 or 3 cm. below, illustrates the wet-bulb thermometer adequately. Show that a current of air playing over the covered bulb affects the reading.

**89**, § 137. For a diagram of the cryophorus, see Watson, Fig. 172 (p. 257), where some comment on its relation to distillation can be found.

**90**, § 137. The allusion here is to the experiment of freezing water within the exhausted receiver of an air-pump, very strong sulphuric acid being employed to absorb the water-vapor continually, and thus encourage evaporation. Insist upon the real reason why the air needs to be exhausted.

**91**, § 149. See Chute, p. 168 (281), for the general idea; but the details are given better by Tyndall, Heat, p. 46.

**92**, § 154. The allusion here is to the radiometer, whose response to sunshine should be exhibited.

**93**, § 155. Effects of radiation from a stove, a fireplace, and "heated objects" generally to be shown by means of a thermometer, and perhaps a radiometer; but, in the interests of simplicity, not with a thermopile and galvanometer at this stage.

**94**, § 155. The stock experiments in radiation are represented well enough by Chute, pp. 153–159. This is one instance where a particularly large margin must be left to the discretion of the teacher. But he should not allow himself to use — nor to countenance — the phrases, "Radiant heat," "Radiate heat" (see § 154, the closing paragraph). For ordinary conditions, the experiments may perhaps be confined to the points covered by Chute, p. 153 (258), and p. 157 (265). There is an excellent vacuum inside a good electric glow-lamp, and the heating of the glass answers the question of Chute, p. 155 (261).

**95**, § 157. Many of the experiments still current on the subject of (thermal) conductivity are weak in omitting entirely to include the modifying influence of specific heat, or in passing that element by with incidental mention (compare Madan, Heat; Conduction, pp. 242–246). Keep this in mind, and see Chute, p. 133 (217); p. 135 (222). Such experiments are comparative only where the specific heats of the substances are nearly equal.

**96**, § 160. A bicycle wheel, with its ball-bearings and grooved rim, is a good ready-made "wheel," and "axles" of various radii can be attached to it easily.

The work-unit is prevalently defined in terms of *resistance overcome*, the word "resistance" being employed in the sense of force opposing the motion, to the exclusion of resistance due to inertia. This is a fair opportunity to offer criticism of that definition in two respects: —

(1) The presence or absence of resistance has nothing to do with the work of a given force that causes the motion. If a block is pulled by means of a spring-balance indicating 500 gr.-wt., and follows the pull for a distance of 30 cm., the work of the pull is $(500 \times 30) = 15{,}000$ gr.-cm., whether the block moves up (against the resistance of its weight) or down, or horizontally, with or without appreciable friction. The *results* of the work are different; more kinetic energy is associated with the block in proportion as the resistances are reduced; but the *amount* of work connected with a given force involves only the two elements specified in Equation (20), § 143. Is it not requisite that these two specifications should be embodied in the fundamental statement about the work-unit?

(2) It is not true, moreover, that "the amount of work done would be one $\left\{\begin{matrix}\text{gram-centimeter}\\ \text{foot-pound}\end{matrix}\right\}$ if you should lift a $\left\{\begin{matrix}\text{gram-mass}\\ \text{pound-mass}\end{matrix}\right\}$ vertically a distance of $\left\{\begin{matrix}\text{one centimeter}\\ \text{one foot}\end{matrix}\right\}$," *unless the speed is the same at the end and at the beginning of the interval.* Suppose, for example, that the bullet of a loaded pistol weighs 50 gr.-wt., and that its distance from the muzzle is 10 cm. If the pistol is fired vertically upward, the work of the force exerted by the powder gases is not $(50 \times 10)$ gr.-cm., but many times that amount, else the kinetic energy could not be stored that carries the bullet to its mark.

This error, or at best this ambiguity involving the awkwardness of defining the unit of *negative* work (done by weight for *upward* motion), is avoided by adhering to the scheme of the text.

**97**, § 160. The inclined plane. Chute, p. 100 (148); and compare the details of Stone, pp. 281–285.

**98**, § 161. Chute, p. 77 (118); and connect his (119) with § 162 of our text.

**99**, § 164. Chute, p. 73 (112).

**100**, § 166. The essential relation used in the text can be obtained most simply and surely (so far as I know) with the contrivance shown in Fig. 106. This method was devised seven or eight years ago by Professor Whiting, and has stood trial. A wooden bar *AC*, from 150 to 400 cm. long, and perhaps 2 cm. by 5 cm. in cross-section, is suspended by a flexible hinge of cloth or leather from a fixed support *S*. Its time of beat as a pendulum is obtained by noting the interval covered by 50 or 100 swings. The bar is drawn aside by a thread attached near *C*, and carried over fixed pegs 3, 2, 1, to the ball of lead *B*, whose weight is sufficient to hold *AC* in the position shown. On burning the thread, *B* falls, and *AC* swings toward the vertical. A strip of "carbon paper," backed by white paper, covers the face of the bar near *C*; and matters are adjusted so that *B* strikes the carbon paper, printing a dot. In half the time of one beat for *AC*, therefore, the centre of the ball falls through a measurable vertical distance. The beat of *AC* can be regulated by a slider of lead.

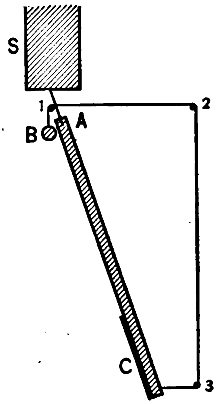

Fig. 106.

**101**, § 174. Chute, p. 92 (137); with a query as to the heading "First" (p. 93), because any apparent variation of period would probably be illusory.

**102, § 175.** Beside some ordinary qualitative illustrations of inertia, it is desirable to carry out a measurement of mass that will help to disconnect that quantity from weight. One method of doing this is suggested by Fig. 107. The brass wire $W$ is chosen of such length and thickness as to give a suitable period of vibration (say 2 to 4 seconds) with the attached masses. The wooden bar $B$ is 15 to 20 cm. long, with cross-section that stiffens it, and carries the cylindrical cups, $C$, $C_1$, at equal distances from $W$. Equal cylinders of zinc fit the cups snugly. These cylinders may be replaced by others of equal radius (but different altitude), or by *fine* shot, the adjustment being always to equal time of vibration. The altitude of a cylinder does not affect its moment of inertia for an axis parallel to its own at a given distance, when the mass and radius of the cylinder are also given. Hence equal times of beat in this case mean equal masses in the cups (Watson, p. 94).

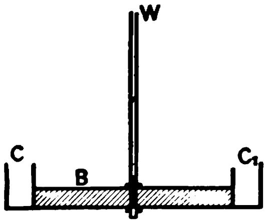

Fig. 107.

**103,** § 177. The intention here is that density should be determined in two or three cases, by measuring the *mass in grams* (with an equal-arm balance) and the volume in cubic centimeters. The density is then strictly the quotient of the *mass* by the volume.

There can be no doubt that the distinction between weight and mass is not understood, if put at the threshold of the subject, as is sometimes done. See the wise remark of Professor Cajori in his "History of Physics" (p. 53). And it is better to leave such questions untouched than to slur them over, at the beginning or elsewhere, with a

definition of mass as "Quantity of matter," or of density as "The *weight* of one unit of volume of the substance." The present text postpones the introduction of mass as a quantity (and therefore of density) to a stage of the course where, as I believe, the conception can be really grasped, after the deliberate preparation made for it. Specific weight is the more accessible idea for the earlier chapters, and it has been used freely in them.

**104**, § 179. Chute, p. 244 (428); and compare Stone, p. 162 (73).

**105**, § 180. It seems better to measure the speed of sound in air first by a direct method (Stone, p. 161 (72)), rather than by the more indirect methods based on resonance (and stationary waves). Timing an echo from a cliff (or the water in a well) at a known distance is simple, and the reflection of sound can be drawn upon as a familiar experience.

**106**, § 180. The allusion here is not to "Kundt's method," but to experiments that utilize the rails of a railroad track, or a long stick of timber, or two points under water in a pond.

**107**, § 180. Chute, p. 241 (417); and compare Stone, p. 165 (75).

**108**, § 181. Chute, p. 261 (472).

**109**, § 181. Chute, p. 243 (426). Connect with this Stone, p. 170 (77), as showing another mode of alternation.

**110**, § 184. Chute, p. 245 (434). The "swell" of the sound as the water level *passes* the position of adjustment is a good aid in locating it accurately.

**111**, § 184. Chute, p. 259 (467). The result becomes more striking in proportion as the forks are adjusted care-

fully to unison. Their frequencies should be equal within about one part in a thousand.

**112**, § 185. The form of experiment is sufficiently indicated in the text.

**113**, § 185. Coal-gas (or carbon dioxide) may be substituted for air by displacement, and the new position of strong resonance established. Compare Chute, p. 246 (435).

**114**, § 186. The *qualitative* connection of the note given by a string with (1) its tension, (2) its length, and (3) its mass per unit length. This amounts to a simplification of Chute, p. 263 (476).

**115**, § 192. Chute, p. 287 (511, 512).

**116**, § 193. The constitution of a beam of sunlight entering a room through an opening should be studied carefully. Some details are obscured when the opening is circular, which appear when it is rectangular, like *ABCD* (Fig. 108). Admitting sunlight through such a rectangle, say 5 cm. by 8 cm., study the umbra and penumbra in the shadow of a ruler whose width is equal to *AB*: (1) when the edge of the ruler is parallel to *AD*; (2) when it is parallel to *AB*. Notice that the text insists upon one sense in which sunlight is parallel, and another in which its divergence is 32 minutes.

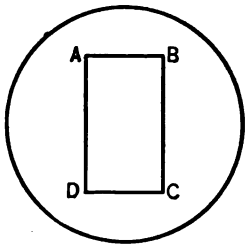

FIG. 108.

**117**, § 194. Chute, p. 290 (517, or 518). The "diffusion photometer" seems worthy of attention for elementary purposes.

**118**, § 196. The general plan implied in the text is that of Chute, p. 298, second method, rather than that of p. 293.

The fact directly established by measurement is, that the line joining luminous point and image is perpendicular to the reflecting surface, and bisected by the latter. The equality of angles is then *proved* as a corollary. The *front* surface of plate glass gives a bright image, and does not complicate thought by the double passage of light through glass, to and from the amalgam.

**119**, § 199. Reflect sunlight from the surface of copper sulphate solution and other colored liquids; from mercury, black glass, and the front face of colored glasses; and from polished (not lacquered) brass and copper. Another instructive example is a dense film of aniline, formed by allowing successive layers of its alcoholic solution to evaporate. Later, the light reflected and that transmitted can be compared for the last case.

**120**, § 200. Chute, p. 300 (530).

**121**, § 201; and **122**, § 202. The cases included in the text can be selected from Chute, pp. 301–303 (532, 534, 535). If it is felt that the single curvature of cylindrical mirrors offers practical advantages, see Stone, pp. 205–211.

**123**, § 203. The relative size of image and object can be included easily in the empirical scheme of the text. Use as object an illuminated opening of known size (*e.g.* 1 cm. square) covered with wire-gauze, and measure the dimensions of its image for several pairs of conjugate distances. The meshes of gauze aid in focussing.

**124**, § 205. The caustic of which the focus is the cusp (Watson, p. 465) is readily shown by allowing sunlight to fall on the inside of a bright cylindrical vessel containing milk ("the cow's hoof in the milk"). The blurring of focus and the formation of focal lines due to oblique incidence can be exhibited on a screen, if the axis of the mirror

is turned 30° to 45° away from the axis of the cone of incident light.

**125**, § 207. It is a good sign that simple methods of measuring index of refraction are multiplying. Chute, p. 305 (539); Stone, p. 217 (95). A third is parallel to that of Experiment 118, so far as locating the image by alignment is concerned. But use a glass cube (paper-weight) to produce the refraction, and a mark on its *rear face* as an object. A tank of transparent liquid may be substituted for the glass, the object being a mark at the bottom, and the measurements being carried out in a vertical plane.

**126**, § 210. The truth of the diagram (Fig. 79) should be illustrated experimentally.

**127**, § 210. Chute, p. 308 (541); and p. 309 (543). The total reflection may be made to disappear, and give place to refraction, by substituting glass for air (541), and water or oil for air (543).

**128**, § 211. Supplement Experiment 127 by measuring this critical angle.

**129**, § 213. This effect may be exaggerated to the point where it amounts to several centimeters, by using a tank of water (small aquarium) with parallel glass sides that are 20 cm. or more apart. Look through the water at a vertical wire, and locate the image by means of a similar wire, employing the adjustment by "disappearance of parallax" (Chute, Fig. 220, p. 298).

**130**, § 214. The production of the two effects named, by the action of a prism on white light. They can be seen "subjectively," the projection of the spectrum on a screen, with the aid of a lens, being postponed. Mark the effect of making the opening through which the light falls

upon the prism narrow, in the direction perpendicular to the refracting edge.

**131**, § 214. Answer this question by producing deviation under *water* with an *air-prism* (air enclosed by three strips of thin, plane glass). Emphasize the thought that the action depends upon the relative speed of light in the (effective) substance of the prism, and in the surrounding medium.

**132**, § 214. (1) The light may be rendered nearly enough homogeneous by colored glass, to give one image of an opening as seen through the prism. Note that such images are most distinct when the prism is at the position of minimum deviation (Watson, p. 476).

(2) It is well to repeat Newton's experiment in some form, recombining the spectrum into white light with a second (similar) prism, or a concave mirror, or a set of adjustable plane mirrors.

**133**, § 215. The (qualitative) result of passing sunlight through lenses of these forms.

**134**, § 215. A companion to Experiment 131. Show that the converging effect of a biconvex glass lens is weakened by using it under water. A biconcave air-lens, enclosed between two watch-glasses [) (], will bring sunlight to a real focus under water.

**135**, § 215. The intention here is to encourage a somewhat independent study of the biconvex lens, following the model of Experiments 121, 122, 123. But see Chute, p. 309 (545); p. 312 (547, 548).

**136**, § 215. With one biconvex lens, produce in sharp focus a real magnified image of any transparent slide or picture. Introduce a second biconvex lens (to represent the condenser) between the source of illumination and the

slide. The lesson will bear emphasis, that the focus is governed by the divergence of the light "scattered" by the slide.

**137**, § 217. The general scheme of the astronomical refracting telescope (and the reflecting telescope?) and the compound microscope seems an eminently proper subject for elementary instruction. See Chute, pp. 326–328 (584, 585). The idea should be insisted upon, that the image formed by the objective is effectively the object for the eye-lens. Catch the real image upon a screen to show its presence, and afterward withdraw the screen. Enlarged "constructions" of the images (to scale) should be made for both lenses.

**138**, § 218. Prism analysis of the light transmitted by colored glasses, transparent solutions of colored salts, alcoholic extract of chlorophyl, etc. It is a good variation to project the spectrum now, illustrating a *use* of biconvex lenses.

**139**, § 219. Let the spectrum of white light fall upon a pure red, or yellow, or blue paper, and note the black (or gray) appearance outside the region of the paper's own color. Highly glazed papers sometimes reflect enough white light to disturb the result looked for. A card with samples of brightly colored dyes is an effective object, when illuminated with a sodium flame.

**140**, § 219. Prism analysis of the light from the sources named in the text (best looked at "subjectively").

**140** *A*, § 220. These effects can be seen on passing a beam of sunlight through milk (diluted if necessary), or through an alcoholic solution of shellac that has been diluted, first with alcohol and then with water, until it becomes slightly turbid.

**141**, § 221. Magnetization by "stroking." Examples of permanent, subpermanent, and temporary (iron or steel) magnets.

**142**, § 222. The distribution of magnetic attraction in a bar magnet can be tested with a tack at the end of a weak brass spring, which is deformed more or less before the tack is separated from the magnet.

**143**, § 222. It is a useful exercise to make a (rough) measurement of the local magnetic declination. All the better if this involves locating the geographical north by means of the pole star.

**144**, § 222. Chute, p. 179 (306). After making the "dipping needle" as there suggested, *use* it to measure inclination. A plumb line and a protractor serve well to obtain the angle.

**145**, § 223. Chute, p. 171 (287).

**146**, § 223. The common device of floating a magnet on a cork.

**147**, § 224. Chute, p. 172 (289, 292).

**148**, § 224. Iron and steel lose (1) their magnetism, and (2) their great permeability, at a red heat. Chute, p. 173 (296); on p. 174, the *nail* is red-hot.

**149**, § 224. Magnetic induction due to the earth is well shown by a strip of "tin" (Professor Crew). Hold it slightly bowed, its length being about in the line of dip, and "snap it straight" two or three times. Polarity can be produced and reversed at will.

**150**, § 224. Chute, p. 171 (288). Repulsion is always the safer evidence of polarity.

**151**, § 225. Chute, p. 174 (300). Compare Stone, pp. 317–320.

**152**, § 226. Chute, pp. 221–222 (378, 379). But test

the action with short magnets (0.5 cm. long) as well. With the current-strength often used in school laboratories for this experiment, it requires *imagination* to trace the circular lines of filings. Note also § 225, the first paragraph.

**153**, § 226. Pass current through dilute sulphuric acid contained in a (horizontal) glass tube, and show the magnetic effect upon a compass-needle. The tube should have a clear diameter of 1 cm. or more to lessen the resistance; but it must be of such length and so placed that spurious effects due to connecting wires are not noticeable. The current-strength required depends, of course, upon how the needle is suspended, and how its deflection is observed.

The magnetic field can be shown, also, round the liquid of a Grenet cell that is put together in a tube bent twice at right angles, giving vertical ends in which the carbon and zinc are placed.

**154**, § 228. Further evidence of magnetic properties in current magnets.

(1) The details of the galvanometer (§ 230) are explained with reference to this experiment. It is therefore a good plan to use the coil of that instrument (Fig. 94) here, removing the magnet *NS*, and sprinkling iron filings on a horizontal sheet of smooth cardboard that reaches across the whole diameter of the coil. The approach of the force lines near the wire to circles, and of those near the centre of the coil to parallel straight lines, is then distinctly visible.

(2) A floating battery is perhaps the most convenient method of showing "set" in the earth's field. Chute, p. 226 (383). But good results can be obtained with a

solenoid (Chute, Fig. 159, p. 224) made of aluminum wire. Suspend it by a silk fibre, to minimize friction, and balance it accurately. Use the upper hook only to make electric connection with a mercury cup.

**155**, § 228. The general truth of Fig. 91 is to be tested with magnet or iron filings, when no iron core is present. Then introduce an iron core, and prepare the way for statements (1) and (2).

**156**, § 228. (1) In showing the attractions and repulsions of current magnets for each other, the earth's influence on the movable magnet can be eliminated by using the *astatic* double rectangle *ABCDE* (Fig. 109). This is constructed of one turn or of several, and suspended by a silk fibre above *A*, while *A* and *E* make electric connection in mercury cups. Or the floating battery can be utilized here, and in exhibiting the action of current magnet toward permanent magnet. See Chute, p. 226.

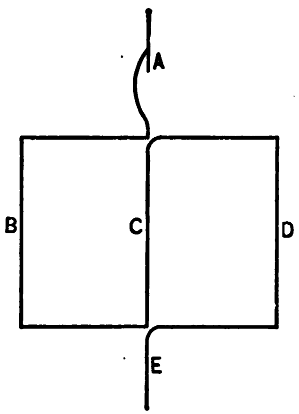

Fig. 109.

(2) The red-hot filament of a glow-lamp can be changed in position by the action of a magnet held outside the bulb.

**157**, § 230. The general idea of the galvanometer, as applied to three forms: (1) that represented in the text; (2) that with fixed permanent magnet, and movable coil (the "D'Arsonval" plan); (3) that of the electrodynamometer, having two current magnets. Include the effect of reversing current, especially as connected with (3). The

reason for using a "short needle" in (1), when it is intended for a "tangent galvanometer," can be made evident from the study of the force lines in Experiment 154 (and see Fig. 95).

**158**, § 232. This topic deserves to hold its place firmly in elementary instruction, as an example of experimental analysis—and not merely because these ideas underlie the dynamo and the telephone. Beside the three variations of conditions numbered in the text, it is well to test the effect of moving the coil while the magnet remains at rest. The conventional directions of the induced currents being indicated by a galvanometer in circuit with the coil, it should be shown by direct trial with a battery cell, what polarity is developed in the same coil by currents of given direction. The facts concerning attraction and repulsion of the magnet and the doing of work (§ 232, first paragraph) are thus put on a firm basis. Chute, p. 227 (386).

**159**, § 232. Extend the conclusions of the preceding experiment to current magnets (Chute, p. 230 (391)), electromagnets (Chute, p. 231 (394)), and the earth (Chute, p. 232 (397)). All these experiments give clear and decisive results, and a galvanometer sensitive enough to show them can be made in any school laboratory.

**160**, § 232. The so-called "eddy currents." Lay such a helix as that shown in Chute, Fig. 163 (p. 227), on its side, and place an iron core in it. Hang a copper disk of about the same diameter as the coil close to one end of the core and parallel to it. *Transient* attractions and repulsions of the disk are noticeable on starting and stopping a current of moderate strength (3 to 5 amperes) in the coil. These are to be brought into relation with the forces made apparent in Experiment 156.

**161, § 234.** For such work as this, the "substitution method" offers the advantage that the galvanometer is adjusted to the same reading always, and the number of assumptions that the pupils are called upon to make in measuring is reduced. The resistance of the wires tested should always be a large fraction of the total resistance in the circuit, and the deflection on the galvanometer should be kept within the range 30° to 60°, if possible. The order of experiments may be somewhat as follows: —

(1) Compare (qualitatively) two wires of equal length and equal area of cross-section, but of different material, the circuit remaining otherwise unchanged. Iron and German silver are a convenient pair. [Dependence on material.]

(2) Compare (again qualitatively) two wires of the same material, with equal areas of cross-section, but having lengths in the ratio of 2 or 3 to 1. [Resistance increases with length.]

(3) Like (2), but the wires are now of the same material and length, and have different areas of cross-section. [Resistance decreases as cross-section increases.]

(4) Use two wires of the same material with *measured* cross-sections, and find the length of each one corresponding to the same deflection of the galvanometer. Both lengths should be of reasonable magnitude. The quotient of length by area of cross-section ought to be the same in both cases. Repeat with different materials, and with different areas of cross-section, in order that a rule may not be made to depend upon one instance. [Resistance is proportional to the quotient of length by cross-section.]

(5) Introduce the idea of "resistance box," and measure a resistance or two in ohms, using the method of sub-

stitution, and the general precautions noted above as regards the range of conditions.

**162**, § 236. Dip two clean lead plates into sulphuric acid, and show that they cause no current in a conductor connecting them. By means of a battery, pass a current between the plates through the acid, and show a *reversed* current after removing the battery. See also Chute, pp. 201–202 (353, 354, 355).

**163**, § 239. Include a Daniell and a Grenet cell in the same circuit, so that their electromotive forces are (1) concurrent, and (2) opposed.

**164**, § 240. Oppose a large Daniell cell to a small one in the same circuit of moderate external resistance, and exhibit the absence of current. Pains must be taken to have both cells in like condition as regards liquids and amalgamation.

**165**, § 240. Stone, p. 334 (140). The Leclanché cell shows similar phenomena in a closed circuit.

**166**, § 240. The allusion is to the polarization of platinum electrodes in sulphuric acid. Compare Experiment 162.

**167**, § 240. Hold the armature of a small electromotor at rest, and note that the current is stronger than it is when the armature is turning fast.

**168**, § 241. (1) Take a primary coil (with iron core) about 30 cm. long, and two coils, each half that length, which can be used as parts of its secondary coil, and which are alike *in all respects*, except that the wire of one is German silver, and the wire of the other is copper. The arrangement must be such that the German silver coil (used alone) gives a distinct induced current through a galvanometer in circuit with it, on reversing the current

in the primary coil. The copper and the German silver coil being in place *together* as secondary coil, no induced current appears if they are connected with each other so that the induced *electromotive forces* in them are opposed. It cannot be a balancing of *currents*, for that excited in the copper alone is much stronger.

(2) Coils of the same material, having different numbers of turns, but otherwise alike, may be arranged "in opposition" to show which induced electromotive force predominates.

**169,** § 241. Use the coils of (2) above separately, and compare the induced currents excited in them under similar conditions.

**170,** § 242. Select two points, $A$ and $B$, on a closed loop in which current is circulating. Attach at $A$ and $B$ the terminals of a (high resistance) galvanometer; and observe its indications as the distance apart of $A$ and $B$ is increased and diminished.

**171,** § 242. In carrying out the plan of the text, let $B$ (Fig. 99) be one storage cell (or two Daniell cells), and $B_1$ be one Daniell cell, "in opposition" to $B$. Then a Grenet cell $B_2$, whose electromotive force lies between those of $B$ and $B_1$, is added, the points $P$ and $Q$ being chosen so that a galvanometer in the loop $PB_2Q$ shows no current. $B_2$ then balances $E_{PQ}$ caused by $B$.

**172,** § 244. Take two coils having resistances in a known ratio, place each in a beaker containing water, connect them in series, and send a current through them, sufficiently strong to heat the water rapidly. If the quantities of water are adjusted until their temperatures *remain* equal as they are heated, the weights of water in the beakers will be very nearly in the same ratio as the resist-

ances. The heat per second developed by the conversion of electrical energy is then proportional to the resistance. The coils may conveniently be of fine German silver wire wound on frames of bone, as in Experiment 173.

**173**, § 244. The coils represented by $A$, $B$, and $C$ (Fig. 110) are alike in all respects, being formed by attaching fine German siver wire in zigzag to frames of bone. The connections $D$, $E$, etc., are of negligible resistance, and are evidently so arranged that $A$ and $B$ carry each half the current that passes through $C$. Each of the coils is immersed in a beaker containing a weighed quantity of water, initially at the same temperature. If the quantity of water round $C$ is only twice that round $A$ or $B$, it will grow hot faster. But the temperature in all three beakers remains nearly the same, when $C$ is surrounded by four times as much water as either $A$ or $B$. This establishes the factor $C^2$ in the rule of Equation (34).

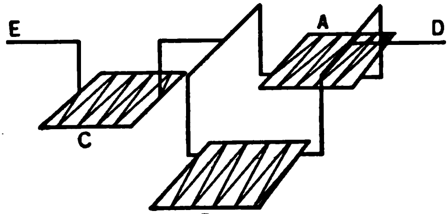

FIG. 110.

**174**, § 246. Chute, p. 180 (309, 310).

**175**, § 246. Chute, p. 181 (312).

**176**, § 247. The point here is the *sharing* of electrification with a second body. Take two pith-balls covered with "gold-leaf," insulate them with shellac *fused* into the form of a slender rod 15 cm. long, and suspend by a silk fibre as a torsion pendulum (compare Fig. 107, p. 374). The balls can be oppositely electrified, and behave accordingly toward other electrified bodies. Introduce also the

gold-leaf electroscope, exciting divergence by *contact* with the knob. Chüte, p. 182 (315).

**177**, § 247. Sparks from sources like the one named, or from an electrical machine. Where it can be done, use the divergent leaves of an electroscope, or the mutual repulsion of two pith-balls hanging by *threads*, to indicate the change of electrification (relief) due to the passage of the spark.

**178**, § 248. Electrification by induction: (1) of an insulated body; (2) of a body that is "earthed." A gold-leaf electroscope succeeds well, if its insulation is under control (Chute, p. 186 (322)). Lead on from these first experiments to the Leyden jar and the electrophorus.

**179**, § 249. It is worth making a vigorous effort to present some experimental evidence connecting the phenomena of electrification with those of electric currents. The material of this chapter loses much of its value unless that is done.

(1) With a sensitive (mirror) galvanometer, whose windings are well insulated, the electromagnetic effect during the discharge of a Leyden jar can be made distinctly visible. It is instructive to charge the jar by means of an induction coil.

(2) Connect the outer coating of a Leyden jar (Chute, Fig. 129, p. 191) with a second knob, distant 4 or 5 cm. from the first, and hang a small metallic bead between the knobs by a silk thread. The discharge of the jar can be brought about gradually by the oscillation of the bead from one knob to the other alternately, under the influence of electrical forces.

**180**, § 249. (1) The physiological effects may be demonstrated in both cases; but care must be exercised to render the shock moderate.

(2) An electroscope connected with one terminal of the secondary coil of an induction coil shows electrification attending the passage of a spark through a few millimeters of air. The induction coil offers several useful "links" between the two groups of phenomena. And the conditions of high voltage with small current-strength have been shown to prevail in it (§ 241).

## MISCELLANEOUS QUESTIONS

[NOTE. — In a general way, these Questions follow the sequence of chapters in the text; though that order is not preserved strictly. Some purely numerical exercises are included, to serve as suggestions. But such examples can be multiplied and varied so readily, that it seems scarcely worth while to put a large collection of them into print. Drill in calculation has value as promoting familiarity with principles and habits of accuracy; yet arithmetical work should be held subordinate here, and connected mainly with fresh data from the laboratory. A more important benefit comes of questions that unfold new aspects of the thought, or add new applications as matters for consideration.]

**1.** Why does a diver need leaden soles to his water-tight suit?

**2.** Why should a "green" log sink deeper in water than the same log when seasoned?

**3.** What fraction of the volume of a floating iceberg projects above the level of the ocean?

**4.** A thin Florence flask is filled with mercury. Is it more likely to break if stood on a wooden table, or on a pillow? After such a flask (full of mercury) has been inverted in a cistern of mercury, is there any tendency for it to break?

**5.** An alloy of lead and zinc is to have the same specific weight as brass. Calculate the proportions in the alloy, supposing its volume to be the added volumes of its ingredients.

**6.** A derrick is capable of raising 10 tons-wt. How many cubic feet of stone (sp. wt. = 2.5) can the derrick lift *under water?*

7. What is meant by saying that a chain is no stronger than its weakest link? [§ 35.]

8. A solid wooden cube is held in the air with its top face horizontal. Reproduce a line of reasoning by which we conclude that the air pressure on the top of the cube is less than that on the bottom.

9. A glass bottle and a flexible rubber bag are both exhausted of air. When submerged in water, each is found to be counterpoised by 500 grams. After introducing 500 gr.-wt. of water into each and placing them under water again, how many grams will be needed to counterpoise (1) the bottle, and (2) the bag?

10. Can a bottle, full of water and corked, be broken easily by driving the cork inward? Why?

11. In Fig. 22 (§ 57), are equal forces exerted upon $D$ by $P_1$, and by the frame of the press?

12. Under what pressure is the gas furnished from your gas-pipes? A gasometer is in the form of a cylindrical tank 8 meters in diameter and 6 meters high, inverted over a pit containing water. Calculate roughly the difference in weight between the tank and its counterpoises, in order to produce the pressure you have measured in the gas.

13. Define the term "Buoyancy" in such a way as to include all the phenomena we have used to illustrate its meaning.

14. A given body is counterpoised by 100 grams in air, by 88 grams when immersed in water, and by 80 grams when immersed in sulphuric acid. What change in length would a column of that sulphuric acid show, when arranged as a barometer, corresponding to a rise in the mercury barometer from 74.9 cm. to 75.6 cm.?

**15.** A rectangular surface is under water, with one pair of sides vertical. Is the average horizontal pressure against the rectangle equal to the pressure at its centre? [§ 44, end.]

**16.** A cylindrical vessel on a horizontal base contains water. How is the distribution of pressure on its walls changed when a piece of wood is put into the water? With the same volume of water, and the same piece of wood, does the result depend on the radius of the cylinder, so long as the wood can be floated?

**17.** Water will not flow from a pipe above the level in an open reservoir with which it is connected. Will gas issue from pipes above the level of the gasometer that supplies them? Why?

**18.** How does it come about that liquid is discharged above its level within the reservoir, in the case of a "soda-water fountain"?

**19.** Water tapped at lower levels in a tank issues with greater speed than if tapped at higher levels. In how far would gas show similar phenomena if tapped near the bottom and near the top of an ordinary storage gasometer?

**20.** Is any difference noticeable in the capillary action of marble toward (1) water, (2) kerosene, and (3) olive oil?

**21.** What other phenomena can you associate with the refusal of a pen to write on greasy paper?

**22.** What evidence is there that cohesion is affecting the shape assumed when a glass rod or a lump of paraffine is softened in a gas-flame?

**23.** Silver is sometimes purified from mixture with lead by a process called cupellation. Inform yourself about that process, and point out the sections of this text that bear upon its chief features.

**24.** Will a piece of cold lead sink or float when put into a vessel containing melted lead? Would you feel equally sure about the result if a piece of cold cast iron were put into some of the same iron in a molten state?

**25.** Supposing that the glass tube is not altered in its dimensions, is the lengthening of the mercury column in a siphon barometer as the temperature goes up an instance of *linear* expansion?

**26.** Give an account from your reading about maximum and minimum thermometers.

**27.** Can platinum be welded like glass and wrought iron?

**28.** Would the numbers in the Table of Specific Heats (§ 117) be changed if the calorie were defined as the quantity of heat required to raise 1 lb.-wt. of water 1° Fahrenheit?

**29.** Why does turning up a lamp-wick increase the size of the flame?

**30.** Explain the appearance of moisture on the chimney of a newly lighted kerosene lamp.

**31.** A body (solid at ordinary temperatures) is at 0° Cent. Given that its specific heat is $s$, its heat of fusion is $f$, and its melting-point is $c°$, express the number of calories required to melt $x$ grams of the solid (starting at 0°).

**32.** If 50 gr.-wt. of ice at 0° are placed in a steady current of steam at 100°, how many grams-weight of steam will be condensed by the time the heat-transfer ceases?

**33.** "The boiling-point of water is the temperature at which it turns into steam." Point out the weakness of this statement.

**34.** Name any important advantages that are apparent to you, which mercury possesses over water as a liquid for use in barometers.

**35.** A vessel contains 600 c.c. of water at its temperature of minimum volume, and the barometer reading is 74.5 cm. How many calories of heat are required (without allowing for losses) to raise this water to its boiling-point?

**36.** Water weighing 800 gr.-wt. at 15° is heated in an open beaker to 98°, and is reduced $\frac{1}{40}$ in weight during the process. What difficulty is there in the way of calculating the heat lost by evaporation?

**37.** Cold dilute alcohol that will not catch fire from a match may be thus kindled if previously warmed. What reason can you state for this result?

**38.** How could you find experimentally the pressure due to water-vapor in the atmosphere at a given time and place?

**39.** What is the office of the "water pan" inside a hot-air furnace? Is there a similar good reason for keeping a vessel of water on a kerosene heater, when it is used to warm a room?

**40.** What grounds can you assign for making a "soldering iron" of *copper?*

**41.** Equal volumes of mercury and of water are heated to the same temperature, and placed to cool under like conditions in similar open vessels. What causes of difference in their rates of cooling can you enumerate?

**42.** Is there any reason why chocolate should cool more slowly than water, starting at the same temperature?

**43.** What is the purpose of the "Davy lamp"? Arrange an experiment to illustrate the important feature in it.

**44.** What properties do you discover in "asbestos" packing that render it suitable for jacketing steam-pipes?

**45.** What physical reasons are there for the choice of material and the general arrangement of an ice-box?

**46.** Are the physical processes that occur properly represented in the phrase, "Icebergs radiate cold"?

**47.** What causes are operative to cool a stream of air as it moves upward from the earth's surface?

**48.** Why is there any tendency of the steam to become "wet" (*i.e.* mixed with particles of water) in the cylinders of a compound engine?

**49.** Express the mechanical equivalent of one calorie of heat in foot-pounds.

**50.** If $M$ (Fig. 50, § 146) falls with quickening speed, what effect does the work of its weight produce, beside heating the water?

**51.** If the heat appearing when 1 gram of carbon is burned in "air" could all be utilized, how many grams of ice would it melt?

**52.** A piece of hot iron remains hot longer if hammered, than if left to itself, other conditions being alike. Account for this effect, and give another instance of similar action.

**53.** Can mass properly be substituted for weight in the statements connected with the calorie and with specific heat (§§ 113–117)?

**54.** Can the term "specific weight" be replaced by "specific density" without error (see § 26, end; § 177)?

**55.** Why are the specific weight (referred to water) and the density of a substance expressed by the same number when we use the metric system? Are the numbers accurately equal, or approximately?

**56.** How is it that a small mountain stream may furnish as much "water-power" as a good-sized river in a flat country?

**57.** Two similar meter-rods are joined together in the shape of a T, and hung up by a string. Where is the string attached, if its direction passes through the centre of weight? What is the consequence of attaching the string at the latter point?

**58.** What general principle includes the observed fact that a plank floats "flat" on water, rather than (1) upright, or (2) on edge?

**59.** In what parts of the text are the general ideas connected with the hydraulic elevator to be found? How would you apply the principle of work to it?

**60.** The specific weight of zinc being 7.1, what is the density of zinc when mass is measured in pounds, and volume in cubic feet? Why are no words put after the value of specific weight, to show in which units it is measured?

**61.** Choose any "simple machine" (*i.e.* lever, pulley, jack-screw, etc.), and show that the quantity of useful work done by means of it is not greater than the quantity of work supplied to it.

**62.** A rectangular table 1.5 meters by 1 meter stands level on legs at the corners, and supports a cylinder weighing 30 kg.-wt. Locate the centre of the cylinder when 5, 5, 10, 10 kg.-wt. represent the shares of its weight sustained by the four legs of the table.

**63.** Given a set of Weights, and a balance with unequal arms, how can you find the weight of a body: (1) if the ratio of the arms is known; (2) if that ratio is unknown?

**64.** A body weighing 250 gr.-wt. hangs by a vertical string 75 cm. long. A second string is attached to the body and pulled horizontally with a force of 150 gr.-wt. At what angle with the vertical will balance occur?

Determine this experimentally, and compare the result with that given by the principle of equal moments (p. 206).

**65.** A uniform bar is suspended horizontally from two vertical spring-balances attached to its ends. A ball weighing 15 kg.-wt. is hung from the bar. The readings of the balance are 10 kg.-wt. and 7 kg.-wt. What is the weight of the bar, and from what point in it is the ball hung?

**66.** Name several instances (beside those in the text) in which it is apparent that sound travels much more slowly than light.

**67.** Will a concave mirror reflect sound to a focus, as it does light? Use the ticking of a watch as a source of sound and try the experiment.

**68.** What instances are known to you (in addition to the ones described already) where higher pitch and more rapid alternation go together?

**69.** Describe two ways in which the note of a tuning-fork may be lowered, giving reasons for your answer.

**70.** A piano-string and an organ-pipe in the same room are tuned to give the same note. The temperature of the room being raised or lowered, they are thrown out of tune. Is the pitch changed in opposite directions for string and pipe; or differently in the same direction; or is the pitch of only one changed?

**71.** How is a piano tuned, and what is the general object to be attained?

**72.** Inform yourself about the method of tuning a pipe-organ, and bring it into connection with some experiments that you have carried out.

**73.** A dry hempen string is stretched between two fixed points, and gives a musical note. Observe whether

wetting the string changes the note, and draw your conclusions.

**74.** After reading Reference 34 (§ 206) draw up a more detailed account of how Roemer's observations led him to his conclusion about the speed of light.

**75.** Make the necessary measurements to settle this point: "Is the angular size of the full moon appreciably greater at the time of rising than it is three hours later?"

**76.** The question is raised: "Does ground glass absorb radiation more than clear glass, or only scatter it more?" What effect of absorption can you use in deciding this question?

**77.** What distinction would you make between transparent materials and translucent ones? Give some characteristic instances of the latter class.

**78.** Why does oiling wood display its grain, and wetting a pebble bring out its color?

**79.** Why do colored glass and colored minerals become whiter when powdered, in proportion as the powder is finer?

**80.** What is the reason why snow and foam are brilliantly white, while ice and water are transparent and colorless?

**81.** Describe the set of images seen when a lighted candle is placed between two parallel mirrors that face each other. Account for this result.

**82.** Light is incident in a fixed direction upon a plane mirror. Prove that the reflected light can be changed 20° in direction by turning the mirror through half that angle.

**83.** How is successive reflection of light from two plane mirrors utilized in the sextant?

**84.** What kind of mirror is used in a laryngoscope? In a Claude Lorraine glass?

**85.** A straight stick partly immersed in water appears bent at the water surface. Explain why the apparent bending of the stick is contrary to that of the light, in passing from air to water.

**86.** Use a rectangular glass tank containing water to find out whether light is always refracted through a 90° prism of water in air, or whether total reflection sometimes takes place.

**87.** Show in section the form of any lenses you have found in use, that are not biconvex nor biconcave. Which are converging lenses? What modification, if any, would the methods of Experiment 135 (p. 289) need, if applied to these lenses?

**88.** What reason is there why a human eye immersed in clear water should not see distinctly? Would the effect be equally troublesome to a near-sighted person, and to one who is far-sighted? What type of lens would remove the difficulty?

**89.** Two similar biconvex lenses of glass are placed in air, and have a common axis. The focus of light that has passed through both is found to be as far from the second lens, as the source of light is from the first. Describe two arrangements of the lenses that fulfil this condition.

**90.** After looking through a telescope at a distant object, do you push the eye-lens in, or draw it out, in focussing for a nearer object? Why?

**91.** It is required to form an image having four times the area of the object, with a biconvex lens of glass whose focal length is 25 cm. in air. How would you go ·ut it?

**92.** Take an opera-glass apart, and give an account of the lenses used in it. How is the position of the eye-lens related to the focal length of the object-glass? Trace in detail the formation of the image seen by one eye.

**93.** If you look through a glass prism at an opaque object (like a window-bar) against a bright background, why do you see colored fringes? Account for the relative position of the colors. Why do the colors not appear all over a window-pane of ordinary size?

**94.** Why would you expect lenses to produce dispersion of white light? Arrange an experiment to show that such dispersion is actually produced.

**95.** Of what color does a red rose appear when looked at through blue glass?

**96.** A concave mirror or a biconvex lens converges the *energy* of sunlight at its focus. What phenomena support this statement?

**97.** Put together such points of likeness and difference as you recognize between sound and light.

**98.** Two steel bars in all other respects alike are magnetized to different degrees. How would you discover which is the stronger magnet without the aid of any third magnet but the earth?

**99.** A bar magnet is so placed that it just neutralizes the earth's magnetic action upon a short compass-needle. How can this be done? In what way can this idea be used to make a galvanometer show the presence of weaker currents?

**100.** A soft iron rod is supposed to be horizontally before you, and it is required to make its left-hand end a north (north-seeking) pole. Tell accurately how this can

be done by winding about the rod a wire connected with the terminals of a Grenet cell.

**101.** What reason can you assign why the wire of a telephone circuit should not be placed parallel to the wire of an electric light and power circuit, and near it? Which is worse for the telephone, alternating or "continuous" current in the other wire?

**102.** A flexible wire carries a steady electric current. In what way would you arrange or wind the wire to secure greatest magnetic effect in its field; and how can its field be almost entirely disguised?

**103.** Name four typical phenomena producible with a steel magnet, and describe how each one can be brought about also with a contrivance containing no iron or steel.

**104.** A battery cell causes a given current-strength in a wire joining its terminals. Why does the addition to the circuit of an exactly similar cell (in series) not precisely double the current-strength? Can the current-strength be doubled by adding the second cell in parallel with the first?

**105.** How would you find the current-strength corresponding to any reading on your galvanometer?

**106.** Given that the electromotive force of a Daniell cell is 1.05 volts, how would you measure the electromotive force of a storage cell or a Grenet cell?

**107.** Why may a piece of wire be fused when placed in circuit with one storage cell, though the wire is not fused by the action of three Daniell cells?

**108.** How is it that a given current-strength causes a wire of lead to melt, where a platinum wire of equal length and cross-section is not melted? What prevents the heat

from *accumulating* in the platinum until its melting-point is reached?

**109.** Under the influence of a "dry wind," it is often observed that one end of a compass-needle rises and adheres to the glass cover. What cause can you assign for this, and how would you make the needle swing freely?

**110.** How do you explain the fact that light bodies are sometimes repelled from an electrified surface after being first attracted to it? Are any particular precautions needed in order that this may happen? What general reason is there, why a magnet does not produce a similar result with iron filings?

**111.** How would you proceed in causing resinous electrification on the inner coating of a Leyden jar?

**112.** The same word "induction" is used in connection with several groups of physical phenomena. Bring these applications of the term together, show in how far they are parallel, and what distinctions are to be made among them.

**113.** The discharge of a Leyden jar is often accompanied by a bright hot spark. Where does the heat of the spark come from?

**114.** What is the physics of a lightning flash, as you understand it? What causes the "thunder peal"? Do you connect Benjamin Franklin's work with our knowledge on either of these points?

# INDEX

[NOTE.—This Index has been made fuller than usual, in order that it may prove useful in tracing connections among different parts of the book, and supplementing the cross references in the text.]

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